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OBSERVATIONS ON THE DAUBRÉE EXPERIMENT AND CAPILLARITY IN RELATION TO CERTAIN GEOLOGICAL SPECULATIONS

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Those who believe that meteoric waters are an important factor in the production of the phenomena of vulcanism have always met with difficulty in devising a means by which surface waters could reach deep-seated and highly heated regions. This difficulty they have, as they believed, obviated by instancing an experiment made by Daubrée on the passage of water through a porous sandstone against a certain excess counter pressure. That this experiment has no bearing on the question at issue has already been pointed out more than once; but this has apparently not attracted the attention of those who wish to believe in its applicability as a proof of the possibility of introducing accessions of meteoric water into the magma. Accordingly we propose to discuss this experiment and the laws governing capillary processes (of which it is an example); and we endeavor to point out the limitations which must be borne in mind when capillary effects are adduced as important factors in the production of geological phenomena such as vulcanism.

Daubrée's experiment.—In this experiment, which was performed in 1861, Daubrée found that water would pass through a disk of

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sandstone, 2 cm. in thickness, in spite of a certain excess counter pressure of steam; his apparatus is represented[1] schematically in Fig. 1. A disk of Strasburg sandstone was clamped between two chambers, the upper one (L), open at the top, containing water, the lower one (V), gas-tight and connected to a stop-cock (C) and manometer (M). The whole rested on carbon blocks, and was

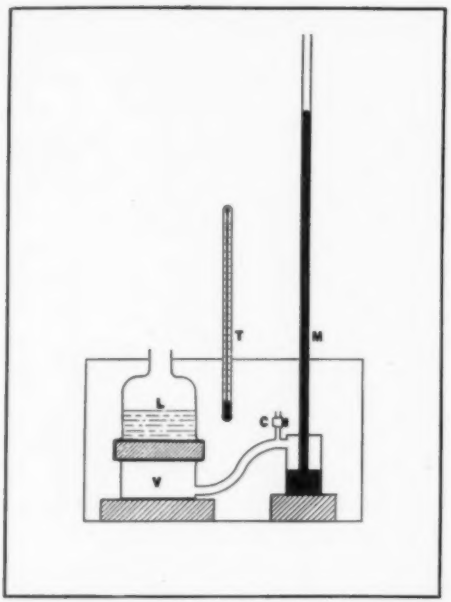

FIG. 1.—Diagram to illustrate the form of apparatus used by Daubrée

placed inside a loosely-closed metal box heated from beneath. Daubrée caused the temperature in the inside of the box (as measured by the thermometer T) to remain for some time at 160°, the cock C being open meanwhile. Upon closing C he observed that the mercury column rose gradually to a height of 68 cm. (0.9 atm.). On relieving the pressure by opening C, and subsequently closing it again, he observed the same effect again.

[1] See Daubrée, *Géologie expérimentale*, Paris, 1879, p. 238.

The water was therefore passing through the sandstone against pressure.[1] Daubrée attributed this phenomenon, and rightly, to capillary action, but apparently he was without a clear conception of the physical principles involved; consequently his interpretation of the experiment is in part erroneous and some of his conclusions indefensible. Thus he writes:[2]

> Supposons une cavité séparée des eaux de la surface, marines ou continentales, par des roches qui ne soient pas tout à fait imperméables; admettons, en outre, que cette cavité soit à une profondeur assez grande pour que sa température soit très-élevée: les conditions principales de notre expérience ne se trouveraient-elles pas reproduites? De la vapeur s'accumulerait donc dans cette cavité, et sa tension pourrait devenir bien supérieure à la pression hydrostatique d'une colonne liquide qui remonterait jusqu'à la surface des mers ou des eaux d'alimentation. Et, si l'on est parvenu à mettre en quelque sorte en balance, par l'interposition d'une épaisseur de roche de 2 centimètres seulement, les pressions de deux colonnes, l'une de 2 centimètres d'eau à peine, l'autre de 60 centimètres de mercure, c'est-a-dire de plus de 500 fois supérieure a la première, on ne trouvera plus guère de difficulté à admettre que l'eau descendante devienne la cause du refoulement de laves trois fois plus denses qu'elle, et de leur ascension jusqu'à un niveau bien supérieur au sien. D'après les résultats de l'expérience, l'eau pourrait donc être forcée par la capillarité, agissant concurrement avec la pesanteur, à pénétrer, malgré des contre-pressions intérieures tres fortes, des régions superficielles et froides du globe jusqu' aux régions profondes et chaudes, où, à raison de la température et de la pression qu'elle aurait acquises, elle deviendrait capable de produire de grands effets mécaniques et chimiques.

The "atmometer."—The effect observed is, as Daubrée himself recognized, due to capillarity; similar results may be obtained much more simply and directly by means of the so-called "atmometer."[3] This consists of a somewhat narrow glass tube,[4] open

[1] And against a temperature gradient too, since the upper surface of the sandstone was at 100°, the lower surface at some higher temperature; but the effect of this is, as we shall show, altogether subsidiary, except for extreme temperature differences.

[2] Daubrée, *op. cit.*, pp. 242–43.

[3] Tait, *Properties of Matter*, 4th ed., London, 1899, p. 264.

[4] If a capillary tube is used, a side tube, provided with a good stop-cock, sealed into the wider part of the vertical tube is required in order to enable one to fill the apparatus with water. This form possesses the advantage that under favorable circumstances the rise may amount to several centimeters in the course of a few minutes.

at one end and at the other end made fast[1] to a disk, ball, or other fragment of porous material; the tube is filled with water and inverted in a vessel of mercury (Fig. 2). The capillary effects in

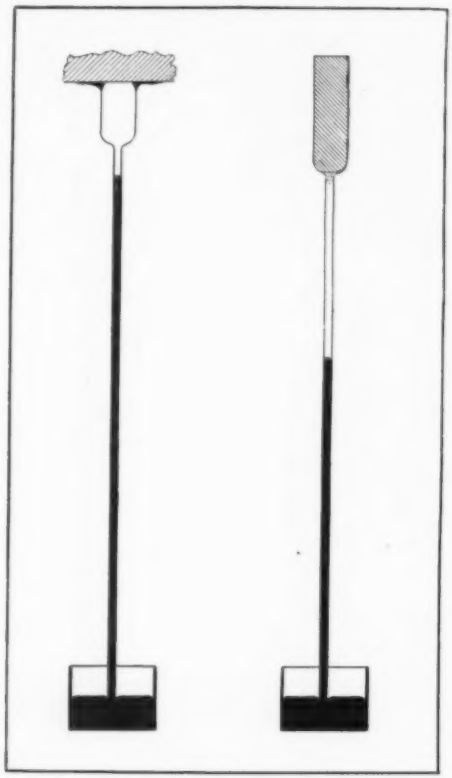

FIG. 2.—Forms of atmometer

the fine pores of the material are such that not only is the water in the tube kept supported but, as evaporation from the surface proceeds, mercury rises to take the place of the water to a height

[1] By means of sealing-wax, beeswax-rosin, or in any other appropriate way. The joint must of course be absolutely gas-tight.

which may equal, or even exceed, the barometric height.[1] The mercury rises gradually—provided that the pores are not too fine—maintains the equilibrium position for some time, and then drops back rapidly; the rate of rise, which depends upon a number of factors, does not concern us here. The position of equilibrium is the important thing; it depends only upon the size of the widest pores at the free surface and the surface tension between water and the porous material; results for samples of various materials, as observed by us, are brought together in Table I. But before considering these results we shall give a brief outline of the theory of capillarity in so far as it concerns the question at issue; for the pores are in effect merely fine capillary tubes.

OUTLINE OF THE THEORY OF CAPILLARITY[2]

The general principle to be borne in mind is that the rise of liquid in any capillary tube is primarily a measure of the pressure discontinuity at the curved free surface of the liquid within the tube.

It can easily be shown that the pressure difference (Δp) between the two sides of a curved surface separating two fluids is expressed by the formula:

$$\Delta p = \sigma\left(\frac{1}{\rho}+\frac{1}{\rho'}\right) \tag{1}$$

where σ is the surface tension and ρ and ρ' the radii of curvature in two planes at right angles to one another. If the surface is spherical, $\rho=\rho'$ and the expression takes the simple form

$$\Delta p = \frac{2\sigma}{\rho}. \tag{2}$$

[1] Thus G. A. Hulett (*Zeitschr. d. physik. Chem.*, XLII (1903), 359, who made experiments of this type using a porous porcelain plate in which copper ferrocyanide had been deposited, observed in one instance a height of 110 cm. of mercury; in this case therefore there was a negative pressure, amounting to about half an atmosphere, acting upon the water close to the under side of the porcelain disk. Similar experiments had previously been made by E. Askenasy, *Verhand. naturh. med. Verein Heidelberg*, March, 1895. This process, it may be remarked, is the commonly accepted mode of accounting for the rise of sap in trees.

[2] Capillarity is treated in any textbook of physics, though not always well. The discussion of it by Tait in his *Properties of Matter* is exceptionally clear.

A slight modification of this formula is directly applicable to the capillary rise of liquids in fine tubes. Consider a tube, open at both ends, partly immersed in a vessel of liquid, which will rise in the tube to a certain height h (Fig. 3). When the rise is several

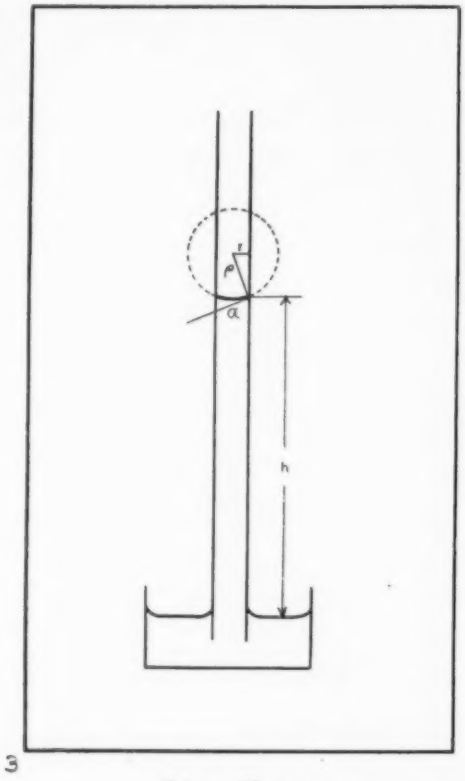

FIG. 3.—Diagram

times the diameter of the tube, the curvature of the free surface in the tube is sensibly uniform; in other words, the surface is a segment of a sphere whose radius is ρ. Now, according to equation 2, the pressure on the under side of the curved surface

is less than that on the upper side by an amount equal to $\frac{2\sigma}{\rho}$; at the same time, however, this pressure difference is equal to the hydrostatic head of a column of the liquid of height h. That is,

$$\frac{2\sigma}{\rho} = h\,g\,d$$

where g is the intensity of gravitation and d the density of the liquid. Moreover, if α is the angle of contact between liquid and tube, $\rho = r\cos\alpha$, where r is the radius of the tube; hence,

$$h = \frac{2\sigma\cos\alpha}{r\,g\,d} \tag{3}$$

which is the familiar formula for the rise of liquids in capillary tubes.

In the case of water in contact with many substances, $\alpha = 0°$ and the equation reduces to the form

$$h = \frac{k\sigma}{r}. \tag{4}$$

For water at a temperature of 18°, provided that h and r are expressed in centimeters,[1] k has the value 0.00204 and σ, the surface tension in dynes per cm., is 74. The development of this formula directly from the basis that there is a definite pressure discontinuity at a surface of separation seems worthy of emphasis since it affords us a clearer insight into the more complicated problems of capillarity.[2] Starting from this basis, a number of conclusions are immediately obvious; we state them here because they have not been

[1] If h and r are expressed in millimeters, the constant k must be increased, not tenfold, but one hundred fold.

[2] Incidentally it may be remarked that by the same reasoning the pressure within a small drop of water is greater than the external pressure; the water is thus under greater pressure than the vapor derived from it. Now this type of pressure—"unequal" pressure—raises the vapor pressure of the liquid; consequently the vapor pressure of a drop is greater the smaller the radius of curvature of its surface—a well-known conclusion which is exceedingly important in regard to a large number of phenomena. In a perfectly analogous way the vapor pressure in equilibrium with the curved surface of a liquid in a capillary surface is smaller than its vapor pressure as ordinarily given; and this lowering of vapor pressure is greater the smaller the diameter of the tube. Similarly (if it be permissible to speak of the surface tension of solids) one may deduce the fact that the solubility of a substance increases as the size of grain decreases.

apparent to all who have adduced capillary effects as a means of accounting for geological phenomena.

(*A*) Since the pressure discontinuity occurs only at the *surface of separation*, a column of liquid (as in Fig. 2, for example) can be supported *only when there is a free liquid surface within the capillary;* in the case of porous materials, therefore, only when there are surfaces of separation within the pores.[1]

(*B*) When equilibrium has been established, the height attained by the liquid in a tube depends only upon the bore of the tube at the surface of separation (since it is this which determines the curvature) and not in any way whatever on the size or shape of the rest of the tube. This statement however by no means implies that liquid will rise in material containing pores of irregular diameter to the height corresponding to the width of pore observed at the surface of a fragment of the material.

(*C*) Consider an open tube, shorter than the height of column of water which it would support, which is filled with water and placed so that its lower end dips below a mercury surface. The free water surface assumes a curvature sufficient only to support the existing column of water; but if water be removed from the top (by evaporation, or otherwise) the curvature becomes greater, and consequently mercury is pulled up into the tube. This process continues until the surface is hemispherical, when it supports a column of mercury and water equivalent in weight to the (much longer) column of water alone which it would support. This is virtually the atmometer, the only difference being that in the latter there are a very large number of pores; we see moreover that the height at equilibrium is determined by the width of the largest pores in the material at the surface of separation.

(*D*) The pressure discontinuity at the surface of separation—which we may look upon as a pressure exerted by the surface film of water in an endeavor to contract itself—is precisely the same in amount whether it make itself manifest (*a*) by supporting a column of liquid; (*b*) by compressing the air in a tube closed at one end and wholly immersed in water; (*c*) in the form of the pressure

[1] This of course includes the case where the liquid in the pores extends practically to the surface of the material as a whole.

required to cause air to begin to flow through a capillary tube (or pore) which originally contained water.[1]

(*E*) The capillary rise is affected by variation of those factors which influence the angle of contact and the density and surface tension of the liquid. The changes induced in the angle of contact and in density may for present purposes be neglected entirely. As regards the influence of temperature on the surface tension of water, all the investigations unite in showing that its surface tension decreases regularly with rise of temperature, becoming zero of course at the critical temperature, where there is no surface of separation. The relation is practically linear when the whole range is considered; it may be represented with sufficient accuracy by the formula

$$\sigma_t = 78 - 0.21\ t \text{ or } 0.21\ (370 - t)$$

where σ_t is the surface tension at t (temp. in Centigrade) expressed in dynes per centimeter.

The effect of pressure on surface tension is unknown, but is presumably small. For the changes in the properties of water induced by a pressure of, say, 1,000 atmospheres are usually similar in magnitude and direction to those observed when a relatively small quantity of a salt is dissolved in it; and the surface tension of such dilute (0.5 *N* or less) solutions differs by only a few per cent from that of pure water.

Experimental.—Before proceeding to the discussion of the geologic implications of the above principles, we shall mention the results of a few experiments on the atmometer principle, carried out with cylinders or fragments of various materials. It may be mentioned that the cylinders of cement and the plaster of paris were cast in glass tubes of appropriate length, which then served

[1] Experiments of this kind have been made by Barus (*Am. Jour. Sci.*, XLVIII [1894], 452), by Bechhold (*Zeitschr. d. physik. Chem.*, LXIV [1908], 328) and by Bigelow and Bartell (*Jour. Am. Chem. Soc.*, XXXI [1909], 1194). The formula connecting pressure required (P, in atm.) with pore diameter (D, in millimeters) is $P = 0.00304/D$ (for room temperature); it is easily derived from formula 3. Bechhold's calculated pore diameters are tenfold too small, a fact which was noted by Bigelow and Bartell. The pressure P is of course not the same as that required to force water to flow through a capillary tube; for in the latter case we do not necessarily have a free surface within the tube.

directly for the experiment; this insured that evaporation occurred, not at the sides, but at the upper surface only. Likewise, evaporation of water at the lateral surface of the sandstones was prevented by coating them with wax. The observations are brought together in Table I, to which we append a few results obtained by Bigelow and Bartell,[1] who determined the air pressure required to just force water out of the pores of the material.

TABLE I

RESULTS OF ATMOMETER EXPERIMENTS WITH VARIOUS MATERIALS

MATERIAL		RELATIVE RATE OF RISE	EQUIVALENT HEIGHT OF MERCURY COLUMN CM.	VIRTUAL HEIGHT OF WATER COLUMN SUPPORTED CM.	EQUIVALENT PRESSURE DIFFERENCE ATM.	CALCULATED DIAMETER OF PORES μ *
Kind	Thickness of Layer Cm.					
"Alundum"	0.5	50	10.5	143	0.14	21
Refractory clay	0.5	75	16.3	222	0.21	14
Pressed magnesia	0.6	35	18.5	250	0.24	12
Porcelain	0.2	100	59.6	810	0.79	3.8
Portland cement	5	20	Did not come to equilibrium; pressure difference at equilibrium presumably greater than 1 atm.			<3
Plaster of Paris	5	20				
Marble	3	5				
Diorite	3	0.1				
Sandstone (Daubrée)	2	.....	.....	.....	0.8	2.7†
Porcelain	—	.....	.....	.....	2.5‡	1.2
Porcelain	—	.....	.....	.....	15.0‡	0.19

* 1 μ = 0.001 mm. The wave-length of the D line is 0.5 μ.

† Direct observations of Bigelow and Bartell.

‡ This result is calculated from Daubrée's data as follows: The pressure of 1.8 atm. recorded by him corresponds, as he himself points out, to a temperature of 113° at the lower surface of the sandstone. At this temperature the surface tension of water is 54.3; the pressure exerted by the capillary curved surface is 0.8 atm., corresponding to a column of water 830 cm. in height. Consequently from equation (4), r = .000134 cm. or D = 2.7 μ.

These results are not especially characteristic of the material; they pertain merely to the particular samples which we happened to use, and correspond to the widest pores in those samples. Moreover we have observed that the differences for layers of the same material of different thickness are no greater than one would expect from the probable variation in size of the widest pores.

From what has gone before, it is obvious that the Daubrée experiment is in principle identical with the experiments just

[1] Bigelow and Bartell, *Jour. Am. Chem. Soc.*, XXXI (1909), 1194. Analogous experiments have also been made by others.

described; that his temperature and temperature difference played no part further than the subsidiary one of decreasing the surface tension of the water and hence the observed pressure difference. Thus it was possible to include in Table I the calculated pore diameter of Daubrée's sandstone as deduced from his values of temperature and pressure difference.

GEOLOGICAL BEARINGS

As long ago as 1881, Osmond Fisher pointed out[1] that the Daubrée experiment was effective merely because there was a surface of separation; and as Kemp,[2] in citing his opinion, writes:

> The experiment gives no ground for thinking that water would move through the heated walls confining a reservoir of molten rock and become involved in the latter.

To quote from Osmond Fisher:

> Capillary action can be made to do great things. . . . . But it cannot cause a liquid to flow continuously through a tube, however short; for, if it could, it would give us perpetual motion. . . . . If there were a cavity filled with vapor, it is possible that the density of the vapor, and therefore its pressure, might be increased to a certain extent, by the evaporation of the water from the extremity of the capillary tubes, and that was what occurred in the experiment of M. Daubrée. . . . . Still further, the existence of capillary communication of water from the surface may be doubted. For if there were supposed a capillary tube extending from the bottom of the ocean, the pressure at the lower end of this tube would be that of the water contained in it *plus* that, if any, arising from capillarity, while the pressure of the crust around its mouth would be that due to the weight of the crust. This latter would be the greater of the two: consequently the liquid upon which the crust rested, having a tension [being subject to a pressure] equal to the weight of the crust, would force back the water in the tube, and if it were not too viscous would itself occupy the tube.[3]

Now it is hard to imagine a permanent configuration, except for comparatively small depths, such that this closing-up of the

[1] Osmond Fisher, *Physics of the Earth's Crust*, London, 1889, 2d ed., p. 143.

[2] J. F. Kemp, "Rôle of Igneous Rocks in the Formation of Veins," *Trans. Am. Min. Eng.*, XXXI (1901), 177.

[3] *Op. cit.*, pp. 144–45. We may note that the argument does not postulate that the material under the "crust" be liquid in the restricted sense of the word; it is valid if the rocks at that depth can flow, a condition which surely obtains except at comparatively shallow depths.

pores by the plastic rock should not occur. Indeed it is hard to conceive of the existence, at any considerable depth, of continuous spaces, unless they be very small;[1] and if they be small and traversed by water, it would appear that they must in a very short time become choked up with material deposited by the water when it evaporates. This point has already been discussed by R. T. Chamberlin,[2] who agrees in thinking that capillary force is quantitatively inadequate; and after adducing various lines of evidence writes: "All of these facts and deductions lead to the general conclusion that our surface-waters have been derived from the interior of the earth, and oppose the idea that to explain the presence of hydrogen, or water, in magmas and rocks, we have merely to appeal to the penetration of surface-waters."

In order to show the quantitative significance of capillarity we present in Table II calculated values of the pressure producible by capillarity at various depths, assuming a temperature gradient of (1) 1° C. per 30 meters, which is about the normal (so far as one can judge from the present very faulty data) (2) 1° C. per meter, which must be nearly the maximum gradient possible, even in the vicinity of volcanoes. In making these computations we have taken into account the variation of surface tension (σ) with temperature, but have neglected the (unknown) effect of pressure; we have also neglected the influence of temperature and pressure (a) on the angle of contact α (b) on the density of water, which enters as a factor (1) in the value of k proper to each temperature and (2) in the calculation of the hydrostatic pressure. In calculating the pressure due to the overlying rock, a mean rock density of 2.7 was assumed. The values given in Table II are therefore approximate only, but nevertheless are amply accurate for the present purpose. Such figures can be used to support geological speculations with regard to the penetration of water into deep-seated rocks only if both of the following restrictive conditions can be considered to be fulfilled: (1) that pores persist to the depth in question; (2) that the rock mass adjoining the mouth of the pore shall be

[1] As to the depth to which spaces may persist, see F. D. Adams, *Jour. Geology*, XX (1912), 97–118, and L. V. King, *ibid.*, 119–38.

[2] "The Gases in Rocks" (*Carnegie Inst. Publication No. 106*, 1908), 70–75.

exposed to a pressure lower than the total pressure to which the water just within the pore is subject. The latter condition would appear to be equivalent to the assumption that, excepting the cases where the capillary pressures are relatively large (i.e., at small depths with very fine pores), the rock mass or magma in question is situated in some sort of cavity, the walls of which protect it from the full load due to the weight of the overlying strata.

TABLE II

TO INDICATE THE MAGNITUDE OF THE PRESSURES (IN KG. PER SQ. CM.*) PRODUCIBLE BY CAPILLARITY UNDER VARIOUS CONDITIONS; THE VALUES GIVEN ARE APPROXIMATE AND SUBJECT TO THE ASSUMPTIONS STATED ABOVE

DEPTH METERS	PRESSURE DUE TO HYDROSTATIC COLUMN	CAPILLARY PRESSURES FOR PORE DIAMETERS OF			TOTAL PRESSURE INSIDE PORES OF DIAM. 0.01 μ	PRESSURE OUTSIDE PORES DUE TO OVERLYING ROCK
		100 μ	1 μ	0.01 μ		
Temperature Gradient, 1° C. per 30 Meters						
100	10	0.03	3.1	306	316	27
200	20	.03	3.0	302	322	54
500	50	.03	2.9	294	344	135
1,000	100	.03	2.8	278	378	270
2,000	200	.03	2.5	250	450	540
5,000	500	.02	1.6	160	660	1350
10,000	1000	.002	0.2	20	1020	2700
20,000	2000	.000	0.0	0	2000	5400
Temperature Gradient, 1° C. per Meter						
50	5	0.03	2.6	264	269	14
100	10	.02	2.2	220	230	27
200	20	.01	1.3	131	151	54
300	30	.005	0.5	50	80	81
400	40	.000	0.0	0	40	108

* 1 kg. per sq. cm. = 0.97 atm.

From this table it is evident that the pressure producible by capillarity is insignificant in comparison with the hydrostatic pressure, except for very fine pores. For each size of pore there is a definite depth above which the combined hydrostatic and capillary pressure exceeds the rock pressure, and below which the rock pressure (presuming that it is fully effective) predominates. For instance, in pores of 0.01 μ diameter and with the normal temperature gradient, the depth at which the opposing pressures just

balance is about 1600 meters; and this depth varies inversely as the pore diameter.[1]

It is evident therefore that capillarity plays a minor rôle unless the pores are very small; and this minuteness of the pores leads us to inquire what amount of water could actually flow through them. This quantity can be calculated by application of the well-known Poiseuille formula, by means of which the rate of flow can be calculated if the radius of the tube, the pressure gradient, and the viscosity of the liquid are known. Hence, assuming the mean viscosity of the water to be 0.005 (its value at a temperature of 30°), the amount of water flowing through a pore of diameter 1 μ (i.e., $\frac{1}{25000}$ inch) would be about 15×10^{-6} c.c. per year; a value which will tend to be too high, since the Poiseuille formula applies to straight pores of uniform circular cross-section, whereas those in the rocks are zig-zag and altogether irregular in shape.

Now if we make the very generous estimate that 10 per cent of the volume occupied by the rock consists of pore-spaces, there will be one million (10^6) pores of 1 μ diameter in each square centimeter. On these assumptions, therefore, the quantity of water flowing would be only 15 c.c. per sq. cm. of surface per year; and the assumptions are such as to tend apparently to make this result too large, rather than too small. But from Table II it is evident that capillarity is quantitatively negligible at any considerable depth in pores of 1 μ diameter; in finer pores, on the other hand, where the pressure producible by capillarity is relatively important, the quantity of water in flow is absolutely insignificant. Thus, if the diameter of the pores is (*a*) 0.1 μ (*b*) 0.01 μ, and on the assumption again that the proportion of total pore space is 10 per cent,[2] the amount of water flowing would be (*a*) 0.15 (*b*) 0.0015 c.c. per sq. cm. of surface per year. In the latter case, in other words, a period of 1,000 years would be required for a quantity of water equivalent to 1.5 cm. (about one-half inch) of rain to flow past a given horizontal plane; moreover, the adoption of any reasonable assumptions other than those used above would not, we feel sure, increase these calculated values more than tenfold. In connection with this, we would remark only that water percolating

[1] At least, this is true with sufficient approximation for the present purposes.

[2] This corresponds to (*a*) 10^8 (*b*) 10^{10} pores per sq. cm. of surface.

into a magma (presuming for the moment that it is possible) at this rate would be very little likely to produce any very violent effects.

The foregoing statements, of course, by no means imply that water cannot, and does not, penetrate, by capillary action or otherwise, to a considerable depth into the upper and cooler layers of the crust of the earth. Indeed the preceding figures and arguments tend to show that water would be likely to occur in appreciable quantities down to depths of about 500 meters (1,500 feet) and in minute quantities down to perhaps 1,500 meters (5,000 feet)—a conclusion which is, we believe, entirely borne out by experience.

CONCLUSION

The Daubrée experiment on the passage of water through a disk of sandstone against a certain counter pressure of steam is, as has indeed been pointed out by others, an example of the effects producible by capillarity. The same effect may be obtained, and much more simply, by atmometer experiments such as we describe. The magnitude of the possible effect under various conditions may therefore be deduced from the laws of capillarity. Capillary forces are effective only when there is a surface of separation within the pores; moreover they diminish steadily with rise of temperature, and vanish at the critical point of the liquid. Calculation shows that the effects producible at any considerable depth are, in comparison with the pressure due to the hydrostatic column, insignificant except in pores of such fineness that the amount of water which could flow through them is infinitesimal.

It appears therefore as if the probabilities were all against the notion that appreciable amounts of meteoric water can ever penetrate into deep-seated and highly heated rock masses. We feel therefore that the burden of proof should now be imposed on anyone who asserts the contrary, for, even if some unconsidered factors intervene to upset the calculations of the foregoing pages, he would still be confronted with the difficulty of imagining a reasonable configuration of the rock in depth, such as would insure that the total pressure within the pore is not overbalanced by the pressure to which the plastic rock surrounding it exerts.

THE VOLCANOES AND ROCKS OF PANTELLERIA

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PART III

PETROLOGY

Chemical characters.—All of my analyses of the Pantelleria rocks, with their norms, are given in Tables I and II. Those of Foerstner are omitted for reasons to be given later. They are sharply divided into a large group with high silica, varying from 63.30 to 72.21, and a smaller, the basalts, with about 46 per cent of silica. So far as known, from Foerstner's publications, my own observations, and Butler's collection, there are no rocks of intermediate composition.

Considering the larger group first, rather high alumina is found only in two or three cases, this constituent being in most of the rocks unusually low for rocks of such moderately high silicity—if the coining of a new word on the analogy of acidity and basicity be permissible. On the other hand, the iron oxides are distinctly high, especially in the pantellerites, going hand in hand with low alumina. Magnesia is uniformly low, as is lime, the latter rarely attaining more than 1 per cent. The alkalies are distinctly high, with soda dominant over potash, the latter being remarkably uniform. Titanium is remarkably high for rocks of this silicity and alkalinity. Phosphorus and manganese are both rather above the normal, but zirconia is low for sodic rocks, and only traces of barium are present. Traces of nickel seem to be commonly present, but tests failed to reveal the copper reported by Foerstner.

The basalts are very uniform in composition and show only one especially noteworthy character—the high titanium content.[1] Magnesia is not high for basalts of this general composition (camptonose) and alumina is distinctly low, much lower indeed than the

[1] H. S. Washington, *Q.J.G.S.*, LXIII (1907), 76.

TABLE I

Analyses of Pantellerian Lavas

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
SiO_2	65.27	63.43	63.30	64.54	63.77	72.21	70.14	69.79	67.32	69.91	66.07	69.33	67.85	46.40	46.22	45.72	44.83
Al_2O_3	13.50	16.31	16.38	11.49	11.18	9.72	8.61	11.91	9.55	8.58	11.74	8.62	12.87	14.34	12.23	12.45	11.73
Fe_2O_3	4.40	2.04	2.54	5.14	5.02	3.26	6.01	5.35	6.73	1.81	2.05	2.65	1.84	4.09	4.91	1.57	1.35
FeO	2.52	3.14	2.36	2.99	2.58	1.07	2.73	1.43	0.81	5.86	5.88	5.52	4.54	8.22	7.71	12.01	11.79
MgO	0.55	0.78	0.84	0.89	0.51	0.29	0.20	0.25	0.20	0.28	0.13	0.52	0.30	7.00	6.74	5.29	5.50
CaO	0.85	1.70	1.62	0.64	1.37	0.82	0.45	0.25	0.20	0.33	0.46	0.52	0.17	9.85	9.86	9.58	9.63
Na_2O	5.19	6.71	6.36	5.46	5.55	4.42	5.44	5.66	5.71	6.41	6.89	4.78	6.03	3.59	3.39	3.40	3.34
K_2O	4.21	4.31	4.41	4.66	4.35	4.98	4.20	4.59	4.48	4.71	4.80	4.71	4.83	1.00	1.13	1.08	1.40
H_2O+	1.98	0.18	0.83	1.11	2.72	1.96	0.35	0.17	3.15	0.22	0.43	2.35	0.13	0.14	0.17	0.40	0.81
H_2O-	0.14	0.26	0.10	2.12	1.28	0.24	0.17	0.04	0.49	0.13	0.03	0.27	0.02	0.08	0.05	0.01	0.10
TiO_2	1.09	1.19	0.71	0.90	0.94	0.62	0.86	0.89	0.59	0.75	0.92	0.85	0.83	4.54	5.68	6.43	6.88
ZrO_2	.....	0.06	.....	0.08	.....	.....	0.14	.....	.....	.....	0.12	.....	.....	none	.....	.....	.....
P_2O_5	0.17	0.20	0.30	0.16	0.14	0.10	0.12	0.13	0.08	0.16	0.18	none	0.08	0.85	1.46	1.54	2.14
SO_3	.....	0.05	.....	0.17	.....	.....	0.06	.....	.....	.....	0.23	.....	.....	0.12	.....	.....	.....
MnO	0.27	0.04	.....	0.13	0.26	0.05	0.38	0.20	0.24	0.24	0.16	0.27	.....	0.25	.....	0.16	0.20
NiO	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	none	.....	.....	.....	.....	0.15	.....
BaO	.....	0.05	.....	none	.....	.....	none	.....	.....	.....	.....	.....	.....	0.09	.....	.....	.....
SrO	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.03	.....	0.03	.....
	100.14	100.45	99.75	100.48	99.67	99.74	99.86	100.66	99.55	99.39	100.09	100.39	99.49	100.59	99.55	99.82	99.70

A. Trachyte [I(II). 4. 1. (3) 4]. Costa Zichidi.
B. Trachyte [I (II). 5. 1. 4]. Montagna Grande.
C. Trachyte [I (II). $''5.\ 1''.\ ''4$]. Monte Gibele.
D. Pantelleritic trachyte [II. 4. 1. 3]. Costa Zeneti.
E. Pantelleritic trachyte [II. 4. 1. 3′′]. Punta Pozzolana.
F. Comendite [(I) II. (3) 4. 1. 3]. Cuddia Nera.
G. Aegirite pantellerite [II. (3) 4. 1. 3]. Monte Sant' Elmo.
H. Aegirite pantellerite [II. 4. 1. 3]. Costa Zeneti.
I. Pantellerite pumice [II. 4. 1. 3]. Rione Buccarame.
J. Hyalopantellerite [II. 3 (4). 1. (2) 3]. Monte Gelkhamar.
K. Hyalopantellerite [II. 4. 1. 3]. Khagiar.
L. Hyalopantellerite [II. 3 (4). 1. (2) 3]. Cantina Ziton.
M. Pantellerite obsidian [II. 4. 1. 3]. Costa Zeneti.
N. Basalt [III. 5. 3. 4]. Cuddia Ferle.
O. Basalt [III. 5. 3. 4]. Monte Sant' Elmo.
P. Basalt [III. 5. 3. 4]. Dike, Costa Zeneti.
Q. Basalt [III. 5. (2) 3. 4]. Foerstner Volcano, 1891.

TABLE II

NORMS OF PANTELLERIAN LAVAS

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Q	17.10	3.90	5.58	15.12	14.34	31.14	27.60	21.78	22.44	28.38	14.70	28.02	15.36	.....	.....	.....	.....
Or	25.02	25.58	26.13	27.80	26.13	29.47	25.02	27.24	26.69	27.80	28.36	27.80	28.36	6.12	6.67	6.12	8.34
Ab	44.01	56.59	53.97	33.01	33.01	22.01	20.44	35.63	24.10	17.82	33.54	17.82	39.30	28.30	28.82	28.82	28.30
An	0.83	1.67	3.06	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	20.02	14.73	15.57	12.79
Ne	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	1.14	.....	.....	.....
Ac	.....	.....	.....	11.55	12.47	9.24	17.56	10.63	19.40	5.08	6.01	7.85	5.54	.....	.....	.....	.....
Ns	.....	.....	.....	.....	.....	1.10	1.34	.....	0.49	7.08	4.15	3.17	1.22	.....	.....	.....	.....
Di	1.94	4.83	2.48	1.76	5.20	2.57	1.21	.....	.....	0.75	1.24	2.16	.....	18.81	19.54	18.77	17.22
Hy	0.50	1.59	1.96	3.38	1.42	0.46	4.10	0.60	1.03	10.34	9.01	9.28	7.80	.....	8.06	5.74	5.21
Ol	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	9.32	0.28	6.29	6.78
Mt	5.57	3.02	3.71	1.62	0.93	.....	.....	2.09	.....	.....	.....	.....	.....	6.03	7.19	2.32	2.09
Il	2.13	2.28	1.37	1.67	1.82	1.22	1.67	1.67	1.42	1.37	1.82	1.67	1.52	8.66	10.79	12.16	13.07
Hm	0.64	.....	.....	.....	.....	.....	.....	0.32	.....	.....	.....	.....	.....	.....	.....	.....	.....
Ap	0.34	0.34	0.67	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	.....	0.34	2.02	3.36	3.36	5.04

general run of camptonose magmas. The iron oxides, lime, the alkalies, and manganese are about normal, while phosphorus is decidedly high.

The *norms* show some interesting features. The entire absence of anorthite, except in the most salic and most femic extremes, and the poverty in diopside, except in the basalts, are striking, as well as the abundance of excess silica (normative quartz) in all except the trachytes and basalts. Still more striking are the abundance of acmite and the prevalence of sodium metasilicate along with it in all except the extremes just mentioned, and the large amounts of ilmenite.

Foerstner's analyses.—It is always an unpleasant task to criticize adversely the work of another, but in the present case such a course seems to be unavoidable, as Foerstner's analyses, especially of the pantellerites, have been widely quoted and accepted as accurate, being the only ones heretofore available for these rocks. The numerous new analyses, most carefully made according to modern methods, indicate that those given by Foerstner are incorrect and incomplete in certain important particulars, and that many of them are subject to errors, apparently systematic in character. The comparison is shown in the accompanying table.

TABLE III

COMPARISON OF OLD AND NEW ANALYSES

		1	2	3	4	5	6	7	8	9	10
SiO_2	F	61.43	61.47	67.48	70.30	69.61	68.75	68.33	49.87	49.35	44.64
	W	65.27	63.43	70.14	69.79	66.07	69.91	69.33	46.40	46.22	44.83
Al_2O_3	F	17.51	18.09	9.70	6.32	8.02	5.91	10.94	14.80	15.71	12.74
	W	13.50	16.31	8.61	11.91	11.74	8.58	8.62	14.34	12.23	11.73
Fe_2O_3	F	5.11	5.14	7.42	9.23	7.17	5.81	3.74	8.25	7.44	4.21
	W	4.40	2.04	6.01	5.35	2.05	1.81	2.65	4.09	4.91	1.35
FeO	F	2.30	3.06	2.21	1.40	2.83	5.33	5.41	6.88	6.96	11.17
	W	2.52	3.14	2.73	1.43	5.88	5.86	5.52	8.22	7.71	11.79
MgO	F	0.54	1.32	0.77	0.89	0.65	0.08	0.16	6.77	5.71	5.82
	W	0.55	0.78	0.20	0.25	0.13	0.28	0.52	7.00	6.74	5.50
CaO	F	2.45	3.00	1.45	0.84	0.88	2.11	1.36	9.36	9.80	10.12
	W	0.85	1.70	0.45	0.25	0.46	0.33	0.52	9.85	9.86	9.63
Na_2O	F	6.22	5.85	7.21	7.70	7.47	7.52	7.09	2.81	2.96	4.31
	W	5.19	6.71	5.44	5.66	6.89	6.41	4.78	3.59	3.39	3.34
K_2O	F	3.95	2.83	2.94	2.50	2.88	4.28	4.08	0.68	1.31	1.41
	W	4.21	4.31	4.20	4.59	4.80	4.71	4.71	1.00	1.13	1.40
TiO_2	F	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	5.86
	W	1.09	1.19	0.86	0.89	0.92	0.75	0.85	4.54	5.68	6.88

1, 2. Trachyte
3, 4. Aegirite pantellerite
5, 6, 7. Hyalopantellerite
8, 9, 10. Basalt

in which, so far as possible, analyses by both of us of rocks from the same locality or flow are incorporated.

Foerstner's ferric oxide, lime, and soda are uniformly, and often much, higher than mine, except for the lime and soda in the basalts, and the tendency of his magnesia is also to run higher. His alumina is distinctly higher than mine in the trachytes, while in the pantellerites it is generally lower, as it would also be in his basalts were the 4 or 5 per cent of titanium dioxide and phosphoric oxide present subtracted. His potash is markedly lower in the salic group. Only his figures for silica and ferrous oxides run about the same as mine, though even here some great discrepancies are to be noted.

These differences, especially those in ferric oxide, lime, soda, potash, and alumina, are very striking, and so uniformly in the same respective directions as to suggest systematic errors in his analytical methods as the explanation. What these have been it is difficult, if not impossible, to decide definitely, but, without entering into a detailed discussion, they may be ascribed to the inadequate methods prevailing at the time (prior to 1883), and probably in part to impurities in his reagents. It will be noted that his latest analysis, that of the lava of 1891, most closely resembles the corresponding one of mine.

Whatever be the explanation, the discrepancies here pointed out are, for the most part, so serious and so systematic, and the incompleteness so marked, especially as regards titanium, phosphorus, and water, that Foerstner's analyses of the Pantellerian rocks must be considered as of inferior quality and doubtful utility.

Modal characters.—Leaving the basalts out of consideration the lavas of Pantelleria show some very striking modal characteristics. The small amount of quartz, considering the silicity of the rocks, and its great rarity as phenocrysts, are very unusual. Its small amount is, of course, due to the abundance of alkali feldspar and of aegirite. As Na_2O in aegirite takes up four times its amount of silica (molecularly), much less silica is left uncombined than would be the case in a rock of the same silicity but carrying only ordinary pyroxenes in which the ratio of RO to SiO_2 is 1 to 1.

The exclusively alkalic character of the feldspars, and the absolute lack of nephelite and soda-lime plagioclase are very strik-

ing. The soda-microcline phenocrysts very seldom show multiple twinning lamellae or the usual grating structure, but Carlsbad twins of simple individuals are common. The composition, judging from the rock analyses and norms, is somewhat variable, between Or_3Ab_2 to Or_2Ab_3, but will average somewhere about Or_1Ab_1.

Since this paper was written, Dr. H. E. Merwin has very kindly examined optically the feldspar phenocrysts of some of the lavas. In the pantellerites of Zeneti, Khagiar, Gelkhamar, and Cuddia Nera, he finds they have refractive indices (α = about 1.527) corresponding to an albite content of not more than 30 to 40 per cent. We have seen that the average feldspar of these rocks, while somewhat variable, is about Or_1Ab_1, which indicates that the small feldspars of the groundmass are much higher in albite than in orthoclase. The phenocrysts of the Montagna Grande trachyte, however, are relatively higher in albite and approach more nearly to the average composition, Or_1Ab_1. The study of these feldspars is, as yet, but preliminary, and a chemical and optical investigation will be taken up in detail in the near future, but the evidence goes to show that the soda tends to remain in solution longer than the potash.

The abundance of sodic pyroxenes and hornblendes, namely, aegirite, aegirite-augite, cossyrite, and possibly kaersutite, and the poverty in non-sodic augite and hypersthene are also notable. It is also interesting to remark on the absence of *blue* sodic hornblendes, as riebeckite, arfvedsonite, or crossite, riebeckite especially being commonly found in sodic rocks of high silicity. A paper by Murgoci,[1] in which he correlates the presence of riebeckite with zirconium and fluorine as "mineralizers," and katoforite (and cossyrite) with titanium, is interesting in this connection, since on Pantellaria we find titanium high and zirconium low, with no evidence of the presence of fluorine.

It is also noteworthy that only a small part of the aegirite and cossyrite is in the form of phenocrysts, the greater part of these minerals being in the groundmass, or, as is well seen in the hyalopantellerites, not crystallized at all. Here we see the same tendency of the soda to remain in solution as was observed with the feldspars.

[1] G. M. Murgoci, *Am. Jour. Sci.*, XX (1905), 133.

The complete absence of biotite and the great poverty or generally absolute lack of the more salic rocks in magnetite and ilmenite are very characteristic. The rather common presence, though in very small amounts, of olivine in these rocks is interesting. The investigation of Soellner,[1] with analysis by Dittrich, shows that it is an almost purely ferrous fayalite. As is well known, the olivine found elsewhere in highly silicic rocks, as granite and rhyolite, is always fayalite, not common olivine or the magnesian forsterite. The entire absence of nephelite tephrites and basanites is remarkable in view of the highly sodic character of the general magma.

Norm and mode.—The rocks show some interesting relations between the norm and mode. They are quite normative as regards the quartz and feldspars, both soda-microcline and andesine-labradorite, and only slightly abnormative as regards the augite of the trachytes and basalts, and the aegirite of the aegirite pantellerites. The departure of the mode from the norm is, however, very marked in the presence of the sometimes abundant cossyrite and the presence of small amounts of fayalite in the pantellerites.

It is interesting to note that the presence of the soda-hornblende, cossyrite, goes hand in hand with normative sodium metasilicate. In some cases, as in the trachytes, a very little cossyrite is present with neither acmite nor sodium metasilicate in the norm, but in general the amount of this mineral is correlated directly with that of sodium metasilicate in the norm, the rocks richest in cossyrite, especially as phenocrysts, showing most excess of soda over alumina. On the other hand, the rocks, in which aegirite is largely dominant over cossyrite, the aegirite pantellerites, and comendites, show very little or no sodium metasilicate, but, in general, large amounts of acmite in the norm.

This relation between sodium metasilicate and cossyrite, the norm of which shows 8.66 per cent of sodium metasilicate, furnishes an instructive commentary on Harker's[2] criticism that the norm may contain compounds "which are foreign to igneous rocks and some of which are not known in nature." Cross[3] has briefly dis-

[1] J. Soellner, *Zeits. Kryst.*, XLIX (1911), 138.

[2] A. Harker, *Natural History of Igneous Rocks*, London, 1909, p. 365.

[3] W. Cross, *Q.J.G.S.*, LXVI (1910), 499.

cussed this point, and points out that the great majority of the normative mineral molecules are those that Harker himself would necessarily choose.

In many of the rocks now under discussion accurate chemical analysis shows that more than enough soda is present to combine with silica and alumina, or with silica and ferric oxide, as potential or actual albite or aegirite respectively. This excess of soda is an important chemical feature of the rocks and, as among rock-making minerals we find soda always as silicates (except in the sodalite group), it is natural and justifiable to state this excess in the norm as Na_2SiO_3, of course without the implication that a mineral of this composition actually exists. When we find, as we do here, that the rocks showing this sodium metasilicate in the norm are likewise rich in cossyrite, and that this mineral itself contains a large excess of soda, presumably as metasilicate, the procedure adopted seems amply justified. A similar reasoning applies to the other "unnatural minerals" objected to by Harker, kaliophilite, akermanite, wollastonite, and potassium metasilicate. The last of these, by the way, is present in the norms of only three rock analyses.

TABLE IV

AVERAGES OF ROCK TYPES OF PANTELLERIA

	Ia	I	Ib	IIa	II	IIb	III
SiO_2	66.85	69.30	71.75	63.46	66.27	69.08	46.09
Al_2O_3	11.82	11.02	10.23	16.36	13.47	10.58	12.77
Fe_2O_3	5.29	5.12	4.94	2.29	2.20	2.11	2.95
FeO	2.91	2.12	1.33	3.26	4.38	5.50	9.09
MgO	0.73	0.49	0.25	0.81	0.56	0.31	6.17
CaO	1.04	0.78	0.52	1.66	1.02	0.37	9.82
Na_2O	5.32	5.25	5.18	6.55	6.32	6.10	3.43
K_2O	4.71	4.69	4.67	4.37	4.60	4.82	1.16
TiO	0.96	0.88	0.80	0.95	0.90	0.85	5.91
P_2O_5	0.16	0.14	0.12	0.25	0.18	0.11	1.51
MnO	0.21	0.21	0.21	0.04	0.10	0.17	0.20

Succession of magmas.—The change in composition of the magma during the successive eruptive phases offers some features of interest. The averages of the analyses of the several types—each representing a distinct volcanic episode—are shown in Table IV.

They are calculated to 100, free from water and the very minor constituents. The analyses of the comendite and of the Zichidi trachyte are not included, as their place in the succession is uncertain.

I*a* and I*b* are the averages respectively of the early pantelleritic trachytes and the aegirite pantellerites, I being the average of these, representing the composition of the first phase. II*a* and II*b* are the averages of the trachytes and the hyalopantellerites, II being the average of these and representing the composition of the second phase. III is the average of the final basalts, including that of 1891.

The first two phases show a marked repetition in the magmatic succession, a beginning of which is apparently repeated in the basaltic phase. Starting with the pantelleritic trachytes, there is first a rise in silica and a fall in the other constituents (that in K_2O being slight) to the pantellerites which formed the last flows of this phase. After the formation of the caldera the magma returns toward or beyond its original composition, as shown in the fall in silica (and potash) and the rise in the others. Then the change shown in the first phase is repeated, silica and potash rising and the others falling in the hyalopantellerites. After the cessation of these flows the basalts show a change in the magma in the same directions (except the alkalies) but to a greater extent as between phases I and II. The iron oxides do not conform to the courses of the other oxides, but there is a steady increase in the ratio of ferrous to ferric oxide, and first a decrease and then an increase in their total amount. The averages of the whole phases (I and II) show the general trend of the magma to a more femic composition.

In the absence of any accurate data as to the relative volumes of the various types no satisfactory estimate can be made at present of the average Pantellerian magma, but a general consideration of the various flows and cones suggests that probably the average I*a* roughly represents this. If this be so, the order of succession corresponds well with that enunciated by von Richtofen and Iddings, namely: beginning with the mean and ending with an extreme (generally the most femic) after few or more alternations.

The interesting feature about the present case is that the most abrupt changes in the magma seem to be correlated with maxima

of intensity in vulcanicity, marked by the caldera formation and the dislocation of the Montagna Grande block. Far too little systematic study has as yet been made at any volcano of the change in the chemical characters involved in the succession of flows, in connection with variations in the intensity of the volcanic action, to permit any proper discussion or generalization. It may be said, however, that a causal connection between the two seems to be possible.

The general succession is strikingly like that seen in Sardinia, the rocks of which will be described in forthcoming papers. Here we find the pre-Tertiary sheets beginning with rhyolites, passing to trachytes, and apparently ending with basalts. The later large volcanoes of Monte Ferru and Monte Arci also poured out first trachytes and rhyolites, followed by large flows of basalt, which also forms the product of the most recent small cones.

Comparison with other regions.—Rocks analogous to the pantellerites, comendites, and trachytes of Pantelleria are not very abundant, but are quite widely distributed over the earth. The region most nearly like it is that of Afarland and French Somali described by Arsandaux.[1] The resemblance is very close and is emphasized by Arsandaux, who was able to study specimens from Pantelleria also. He describes both lithoidal and glassy pantellerites, which correspond to the two main types on Pantelleria, except for the irregular occurrence of quartz phenocrysts; and also "microgranites," trachytes, and glassy rhyolites with aegirite, riebeckite, and some cossyrite. Except for the occasional presence of quartz phenocrysts and the replacement of cossyrite by riebeckite, the resemblance between these rocks and those of Pantelleria is most striking, extending even to details such as the felt of aegirite needles and small areas of micropoikilitic quartz. Associated with these rocks are basalts of ordinary feldspathic types.

In their chemical features the Somali rocks are like those of Pantelleria, the only notable difference being the smaller amount of soda. Arsandaux did not determine titanium, so we are ignorant as to this.

[1] H. Arsandaux, *L'Étude des roches alcalines de l'Est-africain*, Paris, 1906, pp. 39, 45.

It is of special additional interest to note that, analogously to Pantelleria, the Somali lavas are divided into a large group of pantellerites, rhyolites, and trachytes, with silicity from 76.0 to 66.5 per cent, and a smaller of basalts, the silicity of which runs from 50.1 to 46.2; and that there are no phonolites, kenytes, or other intermediate types here. A further resemblance is that the basalts are "always the most recent of the volcanic series to which they belong." The general silicity of the Somali rocks is higher than that of Pantelleria.

Another analogous region is that of British East Africa, including the Rift Valley, described by Prior,[1] and Mt. Kenya described by Gregory.[2] Both of these geologists call attention to the resemblance of some of the more silicic lavas to those of Pantelleria. These highly sodic rocks are accompanied by plagioclase basalts of ordinary types, though no analyses were made of them. At Mt. Kenya these basalts are the last eruptive products. This region differs from Pantelleria and Somali in the abundance of phonolite, kenyite, and other nephelite-bearing lavas.

Similar rocks have also been described from Eritrea, Abyssinia, Masai Land, Madagascar, Aden, and Sokotra; and farther away they have been met with in Japan, Australia, New Zealand, Germany, and Texas.

Closely allied to the Pantellerian lavas, both chemically and modally, but of paleotypal habit and occurring as intrusive dikes and other bodies, are grorudites, sölvsbergites, and paisanites of Greenland, Norway, Massachusetts, Texas, and elsewhere.

It is a noteworthy fact, bearing on the discussion of the norm on a previous page that sodium metasilicate usually appears in notable amount in the norms of these rocks which carry arfvedsonite, while it is either less or absent in the norms of those which contain only aegirite or aegirite-augite.

Attention may also be called to a feature of igneous rocks which carry aegirite or sodic hornblende, which is in accord with the principles adopted in establishing the norm. This is that such rocks

[1] G. T. Prior, *Min. Mag.*, XIII (1903), 228.

[2] J. W. Gregory, *Q.J.G.S.*, LVI (1900), 205. No analyses given.

only rarely contain soda-lime feldspars, the felsic minerals being almost without exception alkali feldspars, with or without quartz or nephelite. Corresponding to this, the norms of such rocks seldom show anorthite, the apparent presence of this in some cases being certainly due to a too high figure for alumina because of the non-determination of titanium and phosphorus. The norms of such rocks very frequently show acmite, and less often sodium metasilicate, or would show it were the alumina correctly low, while acmite seldom occurs in the norms of any but such sodic pyroxene and amphibole-bearing rocks.

THE STRENGTH OF THE EARTH'S CRUST

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PREFACE

PART I. GEOLOGIC TESTS OF THE LIMITS OF STRENGTH

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PREFACE

The publication of a series of papers on "Diastrophism and the Formative Processes" by T. C. Chamberlin was begun in the *Journal of Geology* in October, 1913. The second part, on "Shelf-Seas and Certain Limitations of Diastrophism," is nearly identical in substance with a portion of a paper read by Professor Chamberlin on August 13, 1913, at the Twelfth International Geological Convention at Toronto, Canada. In this part particularly it is pointed out that the parallel surface and bottom of the shelf-seas, also their occasional extension as shallow water bodies over considerable portions of the continent at certain times, indicate a relation to sea-level and wave base rather than to a delicate isostatic adjustment. The implications of this and other lines of argument given by Chamberlin are toward crustal rigidity, not crustal mobility.

The first four parts of the present article on "The Strength of the Earth's Crust" had been completed before the writer read Professor Chamberlin's paper, or knew that he was at work upon the subject; but the conclusions are so closely in accord with his, though reached by other lines of attack, that this article may be

regarded as a continuation of the same subject, an added contribution in the large field of diastrophism and the formative processes, following out certain of its ramifications.

A somewhat general survey is given here of the problem of the strength of the crust, beginning with the lines of evidence which bear upon it and following out to some degree the conclusions drawn from it. It has in this way been cast into the form of those articles published by the *Journal of Geology* from time to time, under the caption of "Studies for Students."

PART I. GEOLOGIC TESTS OF THE LIMITS OF STRENGTH

INTRODUCTION AND SUMMARY

The capacity of the outer crust to resist vertical stresses is an important field in the theory of dynamical and structural geology. On the one hand, it is known that the larger segments, those of continental and oceanic proportions, rest to a large degree in isostatic equilibrium, the subcrust of the continental areas being lighter than that of the oceanic areas in proportion to the regional elevation. On the other hand, the minor features, those which enter into the composition of the landscape, are known to have been sculptured by external forces and are to be explained therefore as sustained by reason of the rigidity of the crust.

Between these two extremes in magnitude of terrestrial relief lie mountain ranges, plateaus, and basins; made in part by tangential forces, modified by erosion and sedimentation. To what extent can these constructional and destructional forces work in opposition to those other forces which by producing vertical movement make for isostatic equilibrium? The method of attack is from two directions. The geologist examines the structures imposed by tangential forces, the mountains built by igneous extrusion, the surfaces made by erosion, the strata consequent upon sedimentation. From them he may determine the amount of strain which the crust can endure before periodic movements occur in the direction of relief from strain. The geodesist, by means of the plumb-line and pendulum, determines the subcrustal densities and notes the degree to which these are balanced against the relief, pointing

therefore to a relation of flotational equilibrium within the solid earth.

Most geologists in former years have utilized but little the principles of isostasy, as may be seen by reference to the standard manuals. On the one hand, the weight of sediments may be spoken of as the *cause* of downsinking with such equal pace that the condition of a shallow sea prevails for a geologic period, though perhaps accompanied by the deposition of thousands of feet of sediment. On the other hand, and without argumentation to explain the apparent inconsistency, the same geologist may state that tangential forces have built folded mountains miles in height which may be subsequently largely removed by erosion before marked vertical warping of the crust occurs.

In contrast to the geologists, certain geodesists have argued in recent years for a high degree of isostatic adjustment; isostasy being regarded by Hayford, for example, as largely complete in areas probably between one square mile and one square degree in size, the mean departure of these unit areas from the level of complete compensation being stated by him as ranging from 250 to 570 ft. These figures he does not regard, however, as of a high order of accuracy, the latter being probably the more reliable of the two. He states that their significance is mainly in showing that isostatic compensation is nearly perfect. It has even been argued by Dutton, Willis, and Hayford, as an outflow of geodetic studies, that those vertical movements of the outer crust which tend to give isostatic equilibrium are the ultimate causes of the periodic great compressive movements.

There is here between geologists and geodesists a tendency to a fundamental difference of opinion, resulting from the emphasis upon one or the other of those opposing forces which work in the outer crust. The truth must lie within the broad zone between these two extremes of theory. To try to bring them together in harmony is the problem before us.

The first part of the paper, on the geologic tests of the limits of strength, opens with a brief review of the lines of geologic evidence which may be used as tests of the degree of resistance or response by the crust to vertical stresses, having regard to both area and

intensity. Deltas built into deep seas seem best adapted to give quantitative measurements. Those of the Nile and the Niger therefore are subjected to detailed study. They indicate that the earth is competent over those regions to sustain stresses due to sedimentation which are measured by the weight of several thousand feet of rock, even where the load is continuous over tens of thousands of square miles. Whatever response there may be is so slow that the deposition is able to keep pace with subsidence and maintain the load as a permanent stress of this magnitude upon the crust. By analogy the conclusion may be applied to other parts of the earth, and to those negative loads created by the erosion to base-level of regions previously unwarped to an elevation presumably near to that which would give isostatic equilibrium. Consequently, also, the crust should be able to bear in considerable degree the folded and overthrusted structures piled up by the tangentially compressive forces which periodically operate to such large degree within its outer shell. Deeper changes, involving changes of density, are involved, however, in orogenic processes and express themselves in vertical warpings associated with, and following after, folding. This association of vertical and tangential forces complicates the problem of the crustal strength needed to support mountain ranges.

The measures derived from the study of deltas are more in accord with those larger estimates of the strength of the crust obtained by Putnam and Gilbert in 1895 from a transcontinental series of gravity measurements in which was developed and employed for the first time the conception of local rigidity but regional isostasy.[1] Their conclusions have been thought to be superseded and controverted, however, by much more elaborate and complete geodetic studies, first by Hayford, and later by Hayford and Bowie, which went to show that the crust was very much weaker and in much more perfect static equilibrium.

The calculations of Hoskins tended to show also that the crust within the zone of isostatic compensation could not bear permanently loads as great as those apparently imposed by these deltas. If, however, the great hydrostatic pressures within the deeper crust

[1] *Bull. Phil. Soc. Wash.*, XIII (1895), 31–75; *Jour. Geol.*, III (1895), 331–34.

give to it an added resistance to stress differences as great as indicated by the experiments of Adams, then the strains imposed by the deltas may be permanently borne.

This confrontation of the conclusions drawn from various paths of approach raises the problems which are treated in the second part.

MOUNTAINS BUILT BY COMPRESSION OR IGNEOUS ACTIVITY

Mountain ranges made by folding or extravasation must be independent to some degree from vertical forces, but these are not suitable geologic tests of the rigidity of the crust, since it is known, as noted in the introduction, that they are secondarily connected with diminutions of density in the zone of isostatic compensation and in many cases are rejuvenated after partial erosion by later upwarping.

The individual mountains or plateau remnants left standing by circumdenudation, or piled up as volcanic cones are clearly burdens upon the earth. The volume which rises above the average level is a measure of the stress. Gilbert has so used them and obtained values ranging from 40 to 700 cubic miles.[1] These volumes, however, might be called minimum estimates, as may be seen upon examination of their nature.

If a certain broad upwarping reduces the vertical stresses to a minimum and erosion follows without further adjustment, it is the volume of the valleys rather than the mountains which soon comes to measure the larger possible departures from equilibrium. The remaining mountains by their weight produce local downward stresses, but the more regional stresses are upward and are due to the breadth of the field of erosion. These regional stresses will become larger ultimately than the local stresses due to the residual masses.

Volcanic cones do not continue to be built up until their base begins to sink into the crust as fast as the upward growth takes place. On the contrary, their growth ceases when the hydrostatic pressure of the high column of lava or a decadence of pressure in the reservoir below leads finally to a shifting of the vents.

[1] "The Strength of the Earth's Crust," *Bull. Geol. Soc. Am.* (1889), I, 25.

Regional igneous activity has poured out lavas and breccias, burying previous mountainous topography and adding thousands of feet to the outer crust. Lack of simultaneous erosion, as in the Miocene flows of the Columbia plateau, shows that subsidence progressed, perhaps with approximately equal pace. The present altitude of the Columbia plateau is youthful, as shown by the steep canyon walls and undissected interfluvial areas. The initial subsidence accompanying igneous outpouring and the distinctly later upwarping without compression suggest that here isostasy has prevailed. But in such regions the geologic evidence points toward a minimum strength of the crust. The wide area of activity, the numerous vents, the general absence of localization, all are suggestive of widespread fluid rock beneath, magmas which are probably far above the level where the accompanying temperatures are normal. Such conditions would seem to imply the impossibility of the outer crust carrying over such regions the stresses which are possible in regions long free from igneous activity. More reliance as maximum measures of the strength of the crust should be placed therefore upon those external changes which are entirely independent in origin from the interior of the earth locally beneath them.

SHIFTINGS OF LOAD DUE TO CLIMATIC CHANGE

Some of the most striking examples of loading and unloading of the crust are those connected with the climatic fluctuations of the Pleistocene. The continental ice sheet formed, advanced, and retreated rather rapidly, as viewed from the geologic standpoint. As it retreated, the lacustrine and estuarine shores show that the land was rising with the melting of the ice. The upwarping accompanying deglaciation was limited to the approximate region of maximum glaciation and was greatest in the direction where the ice was thickest, in the St. Lawrence valley the maximum uplift being more than 600 ft. These relations suggest strongly an isostatic response to the relief of load. It is not known, however, to what degree the previous downwarp compensated for the burden of the continental ice sheet and what degree of regional stress the crust was able to bear. The lack of close response is seen in that the upwarp continued as a residual movement after the ice departed.

The movement of the crust could not keep pace with the climatic change but it shows by means of these fossil water planes its incompetency to bear without at least partial yielding a burden as broad and as heavy as the Pleistocene climates placed upon it.

Gilbert, in 1889, was led by reflection upon the changes of load imposed by the waters of extinct Lake Bonneville to use them as a measure of the strength of the earth's crust to resist isostatic adjustments,[1] and as previously stated, tested the conclusions drawn therefrom by comparisons with the volumes of mountains made by extravasation, or circumdenudation, or their combination, and of valleys of erosion. Of Lake Bonneville he states:

> Considering the main body of Lake Bonneville, it appears from a study of the shorelines that the removal of the water was accompanied, or accompanied and followed, by the uprising of the central part of the basin. The coincidence of the phenomena may have been fortuitous, or the unloading may have been the cause of the uprising. Postulating the causal relation, and assuming that isostatic equilibrium, disturbed by the removal of the water, was restored by viscous flow of crust matter, then it appears (from observational data) that the flow was not quantitatively sufficient to satisfy the stresses created by the unloading. A stress residium was left to be taken up by rigidity, and the measure of this residuum is equivalent to the weight of from 400 to 600 cubic miles of rock.
>
> From these phenomena and theoretic considerations arises the working hypothesis that the measure of the strength of the crust is a prominence or a concavity about 600 cubic miles in volume.

THE EVIDENCE FROM EROSION CYCLES

Erosion base-levels folded and uplifted tracts, leaving for a time during the process mountains of circumdenudation whose local stresses have previously been discussed. The development of peneplains implies a rigidity of the crust sufficient to prevent responsive vertical movement until after the completion of the cycle of denudation. It may be difficult to determine the original average elevation and the degree of progressive uplift *pari passu* with erosion which preceded the peneplanation, but the fact that broad areas become flat and are controlled until the next deformative movement by the level of the sea suggests that they cannot

[1] *Bull. Geol. Soc. Am.*, I (1889), 23–27.

lie after erosion in close isostatic equilibrium; that whatever stress this implies can be carried by the earth for long periods of time.

The ancient peneplains are now broadly warped and uplifted. The rivers, as a rule, are intrenched in youthful valleys; or their seaward courses are drowned and not yet reclaimed by delta building. These features testify to the recency of world-wide crustal unrest, marked chiefly by movements of a vertical nature; movements which presumably diminished the vertical stresses in the outer portions of the earth and has produced at the present time, as Willis has argued, a higher degree of isostatic compensation than has been customary through the long periods of quiet which separate the epochs of movement.

There are difficulties, however, in using ancient base-leveled surfaces now upwarped as measures of the previous stress. It is known that a region like the Colorado plateaus which now stand markedly high tended to lie near sea-level from the beginning of the Paleozoic to the end of the Mesozoic. Presumably a decrease of density within the zone of isostatic compensation has taken place here during the Cenozoic and the uplift has accompanied or followed the internal change.

Furthermore, if there are stages in the uplift, a considerable volume of rock is removed during each stage, so that at no one time has the average elevation of the region been as high as the residual masses might be thought to imply. Allowing for these qualifications, however, there seems no doubt that the study of erosion cycles will throw light upon the limits of stress due to unloading which the crust can resist, and also upon progressive changes in subcrustal densities through geologic times. This evidence of considerable crusted rigidity, shown by freedom from compensating movements during a cycle of erosion, or by warpings not in sympathy with isostatic stresses during cycles of crust movements, has been pointed out before. Hayford has sought to explain it away by invoking, first, the slight crustal cooling which would occur in regions of erosion because of removal of the upper rock, heating in regions of deposition. Second, he assumes as probable the existence of a high coefficient of compressibility sufficient to make eroded regions rise in appreciable ratio to the thickness of

the load eroded. Third, he assumes a crustal undertow from heavy toward high areas which would not only fold the surface rocks and heat them in the region of undertow but restore the equilibrium of mass in the regions of erosion and deposition.[1] It may be said of all of these factors that when they are subjected to quantitative statement they appear so trifling as to fail wholly to explain the magnitude and breadth and periodicity of crust movements. The inadequacy of the temperature effects has been pointed out clearly by Harmon Lewis.[2] The assumption of the high coefficient of compressibility involves more instead of less difficulty for the high isostasist. The inadequacy of isostatic undertow to account for folding has been discussed briefly by the present writer elsewhere.[3] On the other hand, the control of the level of the earth's surface during epochs of quiet by the forces of planation and not by forces making for close isostatic adjustment has been discussed convincingly by Chamberlin in his present series of articles. It seems clear, then, that in the study of cycles of erosion and deposition much may be determined in regard to the limits of terrestrial rigidity. The subject could be developed further, but it is preferred to place the emphasis of this paper upon the more readily estimated loads produced by the building of deltas.

THE EVIDENCE FROM DEPOSITION

Preliminary statement.—The waters deposit sediment upon the depressed areas of the crust. To what extent may such areas be loaded before yielding of the base and resultant subsidence take place? The geologic record makes it clear that subsidence and deposition are necessarily related. It has been stated often that deposition was the cause and subsidence the effect, the two being regarded as in delicate isostatic adjustment. But this is in reality an assumption, for such a supposed relationship overlooks the extent to which subsidence might have gone forward without deposition and ignores the external load which may have been necessary to

[1] "The Relations of Isostasy to Geodesy, Geophysics, and Geology," *Science*, N.S., XXXIII (1911), 199–208.

[2] "The Theory of Isostasy," *Jour. Geol.*, XIX (1911), 622, 623.

[3] Joseph Barrell, *Science*, N.S., XXIX (1909), 259, 260.

perpetuate and add to a crust movement initiated by internal causes. Sedimentation is dependent upon the rate and continuity of subsidence as well as upon the rate of deposition. Thus, although the sediments give the most complete record of crustal movements, for the distant past it is not easy to separate cause and effect and ascribe to each its part. Where the thickness of sediments, however, is small, as over much of the continental interior, the cause of submergence is presumably almost wholly independent of the local load. Where the sediments are thick and subsidence rapid, as within the geosynclines, the load imposed by sedimentation may on the contrary become the controlling force. It is a particular phase of deposition, however, which will be considered in this article, a study of the load imposed upon the crust by certain deltas. As long as the water plane lies at a constant level the delta builds out at its front. Upon subsidence of the supporting crust the shore retreats inland; less sediment reaches the now submerged front, and the delta in consequence grows chiefly by additions to the shoreward part of its upper surface. The two methods of growth not uncommonly alternate upon the same delta, showing the discontinuity of subsidence. In building outward a delta acquires a convex shoreline. This form is clearly related to aggradation, not to isostatic uplift, and its volume is a measure of a load inclined to further sinking, the larger rivers tending to drain toward and into the downwarps of a continent. To what degree, then, can a region of the crust which is possibly already resisting downward strain bear this added burden? A preliminary examination will be made of several classes of deltas in order to choose those best adapted to test this question.

Most of the deltas of Eurasia and South America are at present advancing rapidly into shallow embayments and the faunas of the continental islands show that the latter were recently a part of the land. The physical and organic evidence thus concur in showing that a very recent subsidence has taken place. It is to be concluded that a submergent phase in the Cenozoic crustal oscillations has marked the short interval since the last retreat of the Pleistocene ice. The great deltas constructed during the late Tertiary and in the Pleistocene are consequently now in great part drowned.

Their location, volume, and limits in most cases are not known. Their modern and smaller representatives, as they build out into shallow water, do not greatly increase the load upon the crust. Deltas recently drowned are therefore not well adapted to serve as tests of the strength of the crust.

Deltas which lie in re-entrant angles of the continents are also poorly adapted to be used as a test. Those of the Indus, the Ganges, and the Colorado are illustrations. As they fill up the heads of gulfs and are without the typical convex outline, it is not only difficult to compute their volume but their situation is such as to suggest that even without the construction of the delta the region might be far out of isostatic adjustment.

Certain rivers, which face the open ocean, such as the Columbia, do not build deltas because of the power of the waves and currents which sweep laterally the fine detritus.

Many rivers, however, build considerable submarine deltas even where the in-planing forces of the ocean prevent a terrestrial outward growth. Such submarine deltas, owing probably to the power of the waves rather than to recent submergence, are marked by convexities in the bathymetric contours opposite the river mouths. The Congo, the Orange, and the Zambesi are examples. These hidden deltas which are built out into deep waters cannot reach more than a certain distance from the shore and part of their detritus is carried laterally along shore by the waves, but nevertheless they possess a very considerable volume and the convexity which they make upon the ocean floor shows to that degree the rigidity of the crust.

The maximum test is found where great rivers have carried forward subaerial topset beds of their deltas over what was previously deep ocean. Fluviatile construction in such examples has dominated over marine destruction, giving a convex outline to the shore; but the subaqueous deposits may still make up the greater part of the volume. Even in these cases the question may be raised whether the deltas have attained the maximum possible size permitted by the strength of the crust. Their size may, on the contrary, be limited even here by the balance of the surface agencies and the limited time during which the river has dominated over

the sea. It is a fair presumption, however, that the largest deltas have reached a size where subsidence keeps pace with added volume.

The deltas of the Nile and Niger.—Only the most powerful rivers, laden with abundant waste and protected by their situation from the heavier wave and current action, can build deltas of this last class directly into ocean basins. Perhaps the two best of the few good examples are those of the Nile and the Niger. Both have built out great deltas from regularly curving shores of the Atlantic type—the type where recent folded mountains do not mark the line between continent and ocean, the type where tangential forces

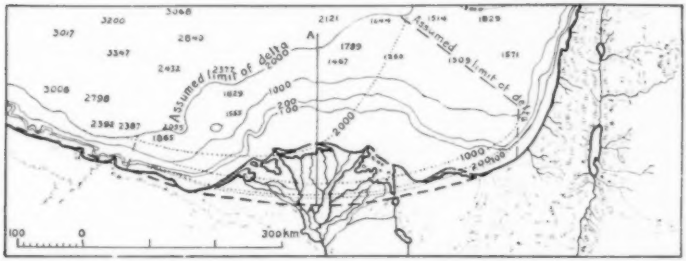

FIG. 1.—Delta of the Nile. Scale 1: 10,000,000. From Andree's *Allgemeiner Handatlas*, vierte Auflage.

cannot be supposed to have disturbed recently the isostatic balance of continent and ocean.

To determine the areas, depths, and volumes of the deltas from the standpoint of isostasy, a smooth curve, as shown in Figs. 1 and 3, was continued through them from the shore beyond. The submarine contours were also projected in dotted lines, giving the form of the bottom as it presumably would now be if no rivers at these places had entered the sea. The volume of the deltas may then be determined by computing the volume included between these two sets of contour lines.

In both cases, in so far as the positions of the hypothetical bottom contours are open to doubt, they have been located somewhat above a most probable position, so as to tend to throw the error of computation in the direction of too small rather than too

large a volume. For instance, the easterly drift of the water facing the Nile delta may have carried considerable mud in suspension to beyond the line assumed here as its limits. In consequence, the hypothetical 2,000-meter contour should be drawn perhaps much closer to the coast of Palestine than has been done. Beneath the Niger delta the contours lie close together on the west but have been drawn as spreading apart toward the east. It would perhaps be nearer the truth to project the steep character of the coastal slopes to the east of the Niger delta under it to where the contours meet the chain of volcanic island mountains extending from the Cameroons out to sea. This appears to be especially probable, since Buchanan has shown that the gentle slopes of the Guinea coast even beyond the limits of the deltas, and extending from

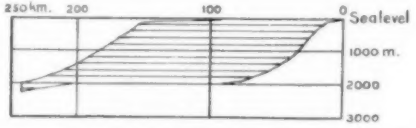

FIG. 2.—Vertical section of the delta of the Nile on *A*-*A*, Fig. 1. Horizontal scale 1: 5,000,000. Vertical scale 1: 200,000. Area of section, 295 kilometers.

long. 2°30′ E. to lat. 8° S., are mantled throughout by very soft, black, oozy mud, characteristic of river estuaries.

All the way down the coast as far as Loanda, lat. 8° S., the same gentle gradients and the same very soft river mud were found. It appears that the land débris brought down by the Niger and Congo, and by other less important rivers, is collected and concentrated in this district. The prevailing current past the mouth of the Congo is a northerly one, while all along the coast from Cape Palmas to the Niger an easterly current sets. These help to confine the drainage matter of both rivers to a comparatively small extent of littoral. If from the soundings west of Cape St. Paul we compute the mean continental slope, we find that the 500-fathom line is at a mean distance of 4.1 miles, the 1,000-fathom line at 11.7 miles, and the 1,500-fathom line at a distance of 17 miles from the 100-fathom line. If it is assumed that in the absence of the Niger and the Congo the continental slope would be much the same as the average found in the profiles west of Cape St. Paul, it may be concluded that the excess of mud forming the flatter talus along the coasts affected by these rivers is due to the mud brought down by them.[1]

[1] J. Y. Buchanan, "On the Land Slopes Separating Continents and Ocean Basins, Especially Those on the West Coast of Africa," *Scottish Geographical Magazine*, May, 1887, pp. 7, 8.

Buchanan states that this gentle bottom slope extends for 1,100 miles along the coast, and computes the volume contained between the steep gradient presumably once existing and the flatter gradient of the present bottom. This represents a deposit of 66,000 cubic nautical miles of detritus due principally to the Niger and the Congo.[1] This great volume cannot be used safely, however, as the measure of a load upon the crust, since a believer in the theory of close isostatic compensation could claim with some degree

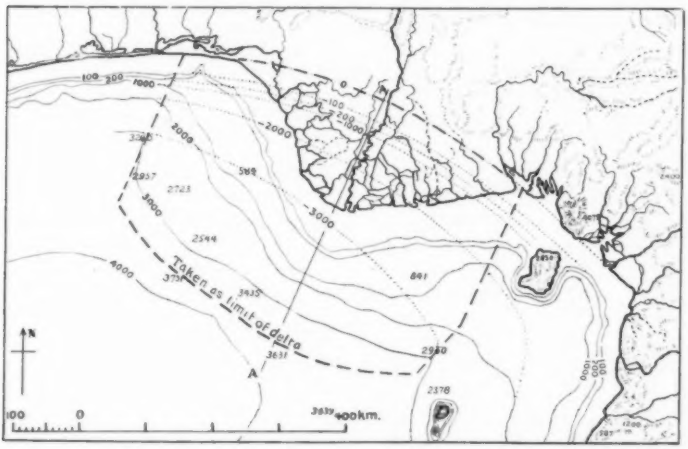

FIG. 3.—Delta of the Niger. Scale 1:10,000,000. From Andree's *Allgemeiner Handatlas*, vierte Auflage.

of reason that the initial slope of the concave shores of the Gulf of Guinea need not have been as steep as the bold convexity of Africa to the west, or that the load may have depressed the bottom so as to have equalized the pressures. Furthermore, Buchanan does not include any of the land area of the Niger delta. The following estimates will give the volume only of the clearly constructional part of the Niger delta, including both the land and

[1] *Op. cit.*, p. 8 and Fig. 3. The volume stated by Buchanan appears to be correct if the two profiles have a common point taken upon the *shoreline*. In his figure, however, the common point A is shown as upon the 100-fathom contour. From this error in the diagram given by Buchanan the volume estimated from the diagram would be much less than 66,000 cubic nautical miles.

the sea portion. But it will be seen, from Buchanan's statements, that this is a minimum estimate of the areal load imposed by the rivers, for a more or less continuous burden on the crust would appear to stretch for a thousand miles along this African coast, reaching a maximum unit value, however, in the great delta of the Niger.

The outer limits of the deltas were taken where the convex slopes fade out into the general ocean bottom.

The results of computing the volumes shown between the two sets of contour lines are as follows:

TABLE I

DELTA OF THE NILE

Area within 1,000-m. contour	71,000 sq. km. (27,400 sq. mi.)
Area within 2,000-m. contour	106,000 sq. km. (38,800 sq. mi.)
Radius of equivalent circle	175 km. (110 mi.)
Equivalence in equatorial square degrees	8.6 sq. degr.
Average thickness within assumed limits	0.84 km. (2,800 ft.)
Equivalence in rock upon land	0.46 km. (1,540 ft.)
Ratio to 76 miles of crust	1 to 260=0.0038
Maximum thickness	2.0–2.3 km. (6,600–7,600 ft.)
Equivalence in rock upon land	1.1–1.3 km. (3,600–4,200 ft.)
Volume within assumed limits (extending on the east to somewhat below 2,000 m.)	89,000 cu. km. (21,300 cu. mi)
Equivalence in rock upon land	50,000 cu. km. (11,700 cu. mi.)

TABLE II

DELTA OF THE NIGER

Area within the assumed limits	195,000 sq. km. (75,300 sq. mi.)
Radius of equivalent circle	250 km. (155 mi.)
Equivalence in equatorial square degrees	15.8 sq. degr.
Average thickness within assumed limits	1.1 km. (3,600 ft.)
Equivalence in rock upon land	0.6 km. (1,980 ft.)
Ratio to 76 miles of crust	1 to 200=.005
Maximum thickness	3.0 km. (9,900 ft.)
Equivalence in rock upon land	1.65 km. (5,450 ft.)
Volume within assumed limits	217,000 cu. km. (52,000 cu. mi.)
Equivalence in rock upon land	120,000 cu. km. (27,000 cu. mi.)

The deltas in their growth had displaced their volume of water. The added loads which they throw upon the crust are measured by

subtracting the weight of the water from that of the sediments. A specific gavity of 2.67 has been taken by geodesists as the average for the outer shell of the earth. The degree of consolidation of the deeper parts of the deltas is not known, but for present purposes the specific gravity of their sediments as a whole may be assumed as 2.50. This will be near the truth if the composition is that of the average shale, if 10 per cent of pore space be assumed and this is wholly filled with water. The specific gravity of sea water is 1.03, leaving an effective specific gravity for the sediments of 1.47. The ratio of 1.47 to 2.67 is 0.55. The thicknesses given for the deltas should therefore be multipled by this factor for estimating the equivalent burdens of rock of specific gravity of 2.67 above sea-level.

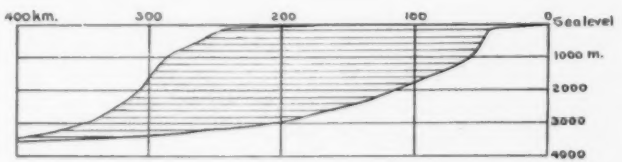

FIG. 4.—Vertical section of the delta of the Niger on *A–A*, Fig. 3. Horizontal scale 1:5,000,000. Vertical scale 1:200,000. Area of the section, 645 kilometers.

It is seen that the deltas are in the form of inclined double convex lenses. Thicknesses approaching the maximum are found over considerable areas in the middle. The load imposed by this thickness is equivalent in the Nile delta to 3,600–4,200 ft. of rock above sea-level; in the Niger delta to 5,000–5,500 ft.

Discussion of results.—The region of the southeastern Mediterranean is held by Suess to be geologically of very recent origin, downfaulted from the continent. The delta of the Nile, much smaller than that of the Niger, is therefore to be regarded as young and may be still increasing in volume.

The great size of the Niger delta suggests, on the other hand, that it may have reached the limit permitted by the strength of the crust. Subsidence may now intermittently keep pace with deposit. If the 1,000-meter contour has been located correctly, as shown in Fig. 3, it suggests that such may be the case, since it is

seen that in contrast to the Nile delta the slopes are much steeper between the 1,000- to 2,000-meter than between the 200- to 1,000-meter contours. This can be explained by assuming that the steep slope lying below and beyond a flatter slope was once a foreset slope just below wave base, whereas it now lies at least 800 meters below. If such a subsidence has occurred, it appears, however, to have been confined to within the limits of the delta; since a peripheral overdeepening of the ocean floor is not evident. On the other hand, it is noted by Penck, but probably too sweepingly, that all bathymetric curves have their steepest slopes between 1,000 and 2,000 meters in depth.[1] Such a phenomenon might be due to lateral flow of sediment under a certain depth of load and without relation to subsidence of the base. The question whether the load of the Niger delta is as great as the crust can bear is therefore an open one.

The Gulf of Guinea, where now the delta is built, is regarded by many geologists as having originated since the Middle Mesozoic by a breaking-down from the continent of Gondwana, but the presence of Middle Cretaceous marine beds skirting much of the coast of West Africa suggests perhaps that the delta in its construction does not go back of the Tertiary. In fact it would seem possible from the youthful relief of the continental plateau that the delta built from its waste is of Upper Tertiary and Pleistocene growth.

A single delta might happen to be a mere veneer of sediment upon an originally slightly submerged projecting part of the coast. Such a fortuitous coincidence of unrelated circumstances may, however, be dismissed as highly improbable in the case of two great rivers draining in opposite directions from the same continent. The conclusion that these deltas are really externally constructive features and measure a real strain upon the crust is strengthened by noting the submarine deltas opposite the other great rivers of Africa, built into the ocean, even though the waves and currents have limited them by preventing their subaerial seaward growth.

In the mechanics of the relation of the delta to the stresses in the crust an important factor is the nature of the marginal land. Shores of the Pacific type have great mountain systems marginal

[1] *Morphologie der Erdoberfläche*, I (1894), 146.

to the continents. Parallel to them the sea has great fore-deeps. It appears as though the mountain ranges had been piled too high by tangential forces, and, by virtue of the partial rigidity of the crust, had depressed the neighboring ocean bottoms. Erosion of the coastal mountains and deposition of their waste in the fore-deep would tend, up to a certain limit, to equalize the strain in the crust. In that case it might happen that, although the mass of the delta measures a stress, this might be opposite in character to pre-existing stresses, with the result that the strain upon the crust beneath the delta before the infilling might be as great or greater, but in an opposite direction. The greatest remaining strain within the sea-bottom could conceivably be an upward strain under the parts of the fore-deep not filled.

Such relations are not found around abyssal slopes of the Atlantic type. These are regarded by many geologists following the lead of Suess as made by marginal downbreaking of the continents. They have but little or no relation to the older folded structures and no excessive deeps parallel to the continental margins. If these relations of the Atlantic and Indian oceans to the continents are rightly interpreted as to cause, it is probable that the stresses which make for downsinking extend beyond the parts already foundered. The margin of continents and ocean basins are not likely to be depressed too low, but if remaining out of isostatic adjustment they would tend rather to stand too high. There is no theoretic reason to believe, therefore, that the Nile and Niger deltas have neutralized pre-existing strains. They are best regarded as real and present burdens sustained by the rigidity of the crust.

Whether or not, however, the building of deltas produced stresses of a character identical with, or opposite to, those previously existing in the region, the stress gradient between the areas of the delta and the surrounding areas would be measured by the weight of the sediments, and this would tend to produce differential flexure. It would seem to be a logical conclusion, therefore, from these tests, that certain parts of the earth's outer crust can resist for considerable periods of time vertical stresses at least equivalent to the weight in air of 10,000–25,000 cubic miles of rock in lenslike

forms spread over areas of 40,000–75,000 square miles and reaching thicknesses in air over considerable areas of 4,000–5,000 feet.

The tabulation of the data regarding the deltas shows the area of the Niger delta to be equivalent to a circle 310 miles in diameter and that over this area the load of the delta is one two-hundredths the weight of the crust to a depth of 76 miles, this being the depth of the zone of isostatic compensation given by the latest determination of Hayford.

According to Hoskins, in a calculation made for Chamberlin and Salisbury,[1]

> a dome corresponding perfectly to the sphericity of the earth and formed of firm crystalline rock of the high crushing strength of 25,000 pounds to the square inch, and having a weight of 180 pounds to the cubic foot, would, if unsupported below, sustain only $5\frac{1}{2}$ of its own weight. This result is essentially independent of the extent of the dome, and also its thickness, provided the former is continental and the latter does not exceed a small fraction of the earth's radius.

The delta, though large, is so limited in size in comparison with continental areas that it would be somewhat more effectively supported, but its externally convex form can hardly be supposed to give it added domal strength, since it consists of more or less unconsolidated material piled upon a concave floor.

The theory of isostasy holds that at a certain depth in the crust there is an approach to equal pressures, the larger relief of the surface being balanced in large part by subsurface variations in density. The larger segments of the crust tend to rise or sink until the elevations are in adjustment to the density beneath. A corollary of this theory is that unbalanced surface loads are largely sustained by the strength of the crust above this level of equal pressures; in other words, but little of the load is transmitted to the deeper earth below. For purposes of discussion it may then be assumed that the load of the Niger delta is supported by the outer 76 miles of crust. This depth is one-fourth of the diameter of the circle equivalent in area to the delta. The load over this area, as stated, is one two-hundredths of the weight of the supporting crust. Allowing something for the limited area of the delta, it is seen never-

[1] *Geology*, I, 555, 1904.

theless to imply a strength of the crust about twice that assumed as a maximum by Hoskins as a basis for his calculation. There are several contributing factors which may explain the disagreement between the figures obtained by observation of the deltas and the calculation given by Hoskins and others: First, part of the stress is transmitted laterally to some extent into the deeper layers, but as the diameter of the loaded area is four times its depth this can be a partial explanation only and has, furthermore, been allowed for. Second, part of the stress may be transmitted into the deeper earth below the 76-mile zone of isostatic compensation. This is about equivalent to third, that the zone of isostatic compensation may extend deeper, at least locally, and fade out more after the suggestion made by Chamberlin.[1] Fourth, a consideration which the writer regards as most important is that the crust may in reality possess greater crushing strength than the 25,000 pounds per inch postulated by Hoskins. At the time that Hoskins made this calculation it seemed that this figure was the highest which could be chosen, since it is higher in fact than the crushing strength of the average surface rock when subjected for even a short time to compression in a testing machine, and in the earth the stresses must be carried for indefinite periods. The experiments by Adams[2] have shown, however, that under the conditions of cubic compression which exist in the earth the rocks are capable of sustaining for indefinite times far higher stress differences than they could bear even for a short time when subjected to stress in one direction only, as at the surface of the earth. These experiments showed that:

> At ordinary temperatures but under the conditions of hydrostatic pressure or cubic compression which exist within the earth's crust, granite will sustain a load of nearly 100 tons to the square inch, that is to say, a load rather more than seven times as great as that which will crush it at the surface of the earth under the conditions of the usual laboratory test.
>
> Under the conditions of pressure and temperature which are believed to obtain within the earth's crust empty cavities may exist in granite to a depth of at least 11 miles.[3]

[1] *Jour. Geol.*, XV (1907), 76.

[2] "An Experimental Contribution to the Question of the Depth of the Zone of Flow in the Earth's Crust," *Jour. Geol.*, XX (1902), 97–118.

[3] *Op. cit.*, p. 117.

It appears then that, even allowing for the great increase in temperature within the earth's crust at depths greater than can be reached by the limitations of experiment, the demands made upon the strength of the crust by the load of the Niger delta are not greater than can be explained by the theory of the mechanics of materials as now understood. This theory rests, however, even after Adams' experiments, upon only a limited range of laboratory observation, and extending over but limited periods only, thus demanding extrapolation both of stress and of time when applied to the whole thickness of the outer crust and over hundreds of thousands of years. Therefore the study of the direct evidence supplied by geologic observation is more convincing in regard to the limits of crustal strength.

These deltas point toward a measure of crustal rigidity capable of sustaining to a large degree the downward strains due to the piling-up and overthrusting of mountains built by tangential forces, or those resulting from the load of sediments in areas of deposition, or those upward strains produced by the erosion of plateaus previously uplifted toward isostatic equilibrium. A final conclusion must, however, await a further discussion in the later parts.

[*To be continued*]

BROILIELLUS, A NEW GENUS OF AMPHIBIANS FROM THE PERMIAN OF TEXAS

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The material upon which this genus is based comprises two specimens, Nos. 684 and 685, University of Chicago, collected by Mr. Paul Miller on Timber Creek, Texas. Both specimens, when found, were almost completely inclosed in hard clay nodules. The matrix has been removed from the surface of the bones very cleanly, but no attempt has been made to separate any of them. The larger and more complete of the two specimens, No. 284, the holotype, includes the complete skull, but very slightly distorted, connected with the complete series of dorsal shields; the right humerus in position with the somewhat crushed scapula; the incomplete clavicular girdle; the incomplete left humerus and a part of the hand; the right femur, tibia, fibula, three tarsals, and two metatarsals. There is also a fragment of the pelvis. Specimen No. 285, of slightly smaller size, has the complete skull less compressed than that of the other specimen. It also is connected with the complete series of dorsal shields, and their corresponding vertebrae; also the clavicular girdle is in place; and an imperfect humerus. Only slight indications of the ribs are present in either specimen.

SKULL

Few other specimens of amphibian skulls in the University collection are in better preservation. The skull is sub-triangular in shape, a little longer than broad, with the face broadly rounded in front. The nares are rather large; they are situated near the anterior extremity of the face, and are separated by about their own diameter. The orbits are rather large, nearly circular in outline, with their hind borders a little beyond the middle of the skull anteroposteriorly. In the middle of each orbit of the larger

specimen there are several osseous plates. Those of the left orbit seem complete; they form a continuous, convex surface, occupying more than half the diameter of the orbit. The plates are five or six in number; they are not arranged in a ring about a pupillary opening, but the surface is continuous. They could not have been sclerotic plates, and it seems not at all improbable that they were merely ossifications in a nictitating membrane, and served for the protection of the eyeball. The parietal foramen is of the usual size

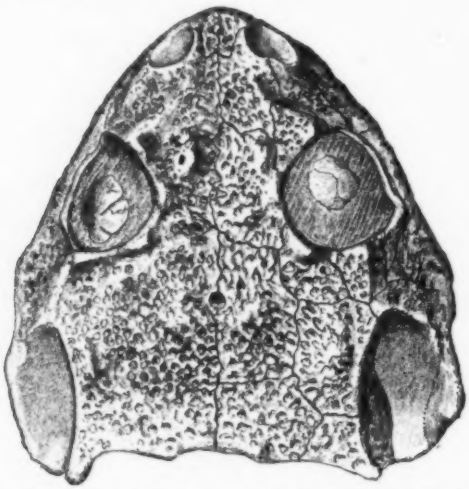

FIG. 1.—*Broiliellus texensis* Williston. Skull, from above, three-fourths natural size. No. 684, University of Chicago.

and is situated a little distance behind a line drawn through the hind margins of the orbits.

The otic notch is large, occupying most of the postero-lateral surface of the skull, and extending forward fully two-thirds the distance to the hind margin of the orbit. The ear-opening itself is rather large, extending forward more narrowly nearly to the front margin of the notch. Below the opening there is a broad, smooth surface, looking obliquely upward, backward, and outward. The excavation throughout is quite like that in the species from New Mexico provisionally referred to *Aspidosaurus* under the specific

name *A. novomexicanus* Williston. It is also like that of *Cacops* except that it is not closed behind. The tabulare is a little elongate posteriorly, but is not turned downward to meet the quadrate, as in *Cacops* and *Dissorophus*.

The surface of the skull is everywhere deeply marked with small, oval, or rounded pits. The most striking characteristic of the species, however, is the presence of numerous tubercular tuberosities, which must have given the animal when alive a peculiar aspect. Each element of the upper surface of the skull has at least one such

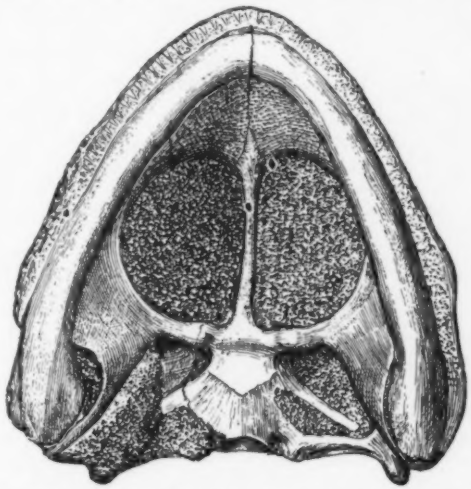

FIG. 2.—*Broiliellus texensis*. Skull, from below, three-fourths natural size. No. 684, University of Chicago.

spiny tubercle, and on each frontal there are at least two. The most prominent ones, however, almost approaching the character of short spines, are situated on the immediate margins of the orbits, one on each prefrontal, frontal, postfrontal, postorbital, and a smaller one below on each jugal.

The sutures throughout are easily distinguishable with the aid of a hand lens as slender, impressed, sinuous, or zig-zag lines. They have been corroborated throughout, not only on the two sides of each skull, but on the two skulls as well, though there is

a slight individual variation in their courses in the two skulls. The shapes and relations of the elements conform so closely to the

FIG. 3.—*Broiliellus texensis*. Specimen No. 684, University of Chicago. One-half natural size.

recognized plan in the temnospondyl skull that a detailed description of them will be superfluous. The lacrimal, as more usual in the temnospondyl skull, extends from the nares to the orbits, as has

been described and figured by Watson, and before him by Broili in *Cochleosaurus*.

The palate has been exposed only so far as is possible in each specimen with the mandibles tightly closed and the clavicular girdle in position. Doubtless the structure throughout is like that of *Cacops*,[1] but the nares and all evidences of enlarged teeth are concealed. The interpterygoidal vacuities are very large, though less elongated than in *Cacops*. Sutural lines for the vomers are apparent, as I have figured them. The whole surface in front, between the mandibles, is covered with minute chagrin-like teeth.

Indications of the stapes, as in *Cacops*, are present, as also the sutural division between the parasphenoid and the exoccipitals.

The sutures of the mandibles, in their closed condition, are not distinguishable. The teeth are shown in both specimens. They are small, pointed cones, of nearly uniform size, throughout.

DORSAL CARAPACE

The general shape of the dorsal shields is shown sufficiently well in the photograph of the larger specimen. In this specimen the vertebrae, with two exceptions, back of the clavicular girdle had been separated and lost before fossilization, as has been demonstrated by excavating the under side in the middle. In the smaller specimen, the vertebrae are all in position as far as the hind end of the carapace, though the last two or three are somewhat disarranged. Furthermore, in the smaller specimen, several of the shields have been cleanly removed from the matrix, proving that they had no connection whatever with the underlying spines; indeed they lie some distance above the vertebrae, with the matrix intervening. The plates in this specimen correspond in number with the vertebrae below, that is, each vertebra corresponds to a single plate and not to two as in *Cacops* and *Dissorophus*. The plates are not of uniform width anteroposteriorly; the third, fifth, and seventh at least are narrower than the intervening ones, which suggested at first that each vertebra had two plates, but this is positively not the case; all of which goes to prove that the plates were entirely distinct from the spines. Indeed the spines, so far

[1] Williston, *Bull. Geol. Soc. Am.*, 249, 1910.

as can be made out, are short and small. The first and last plates are larger than the others, the first subcrescentic in outline, the last oval, with its two diameters nearly equal. The carapace is broadest transversely in front, and tapers to the end. The shields are fifteen in number in each specimen, which singularly is the same number as that of *Cacops*, and probably also that of *Dissorophus*. Each plate is strongly pitted, like the surface of the skull. They are not at all imbricated, but lie side by side, touching each other in both specimens.

APPENDICULAR SKELETON

So far as the clavicular girdles are visible, they show but little difference from that of *Cacops*. The interclavicle and clavicle are smooth externally and are of moderate size; the clavicle has an elongate process for attachment to the scapula. The scapula is for the most part hidden below the carapace; that part which is visible is not unlike the scapula of *Cacops*. The humerus is stouter than in *Cacops*, the extremities are less dilated, and the lateral process is not as stout. What appears to be the right ulna and a part of the hand are shown on the same side of the block as that of the carapace. Six, perhaps seven, carpal bones are seen, together with indications of three fingers, the fifth one with the metacarpal and first phalange in place, the fourth and third represented by fragments of the metacarpals only. The hand clearly was short and broad.

Of the hind extremity, the right femur, tibia, fibula, three tarsals, and two metatarsals are in position. The femur has very prominent adductor crest like that of *Cacops*, but is distinctly stouter than in that genus. The tarsals are probably the third and fourth distalia and a centrale; and the metatarsals doubtless correspond with the distalia. The feet were evidently more elongate than the hands.

As regards the species, it is very probable the genus includes that to which I gave the name *Aspidosaurus peltatus* from the Craddock bone bed. However, inasmuch as there is yet no evidence of a slender inferior process on any of the shields of these specimens, the present species may be provisionally called *texensis*.

It gives me great pleasure to name the genus in honor of my friend Dr. Ferdinand Broili, who has contributed much to our knowledge of the American Permian vertebrates.

MEASUREMENTS

	684	685
Length of skull in midline	92	80
Width posteriorly	85	74
Anteroposterior diameter of orbits	24	20
Interorbital width	27	25
Length of carapace	120	100
Greatest width of carapace	43	36
Length of humerus	46	
Length of femur	54	
Length of tibia	35	
Length of median metatarsal	12	

The present genus is the fifth that has been described of the peculiar "batrachian armadillos" from the Permocarboniferous of Texas and New Mexico, namely: *Dissorophus* Cope, *Cacops* Williston, *Aspidosaurus* Broili, *Algeinosaurus* Case, and *Broiliellus* Williston. The first two of these genera may at once be differentiated by the completely closed otic notch; *Aspidosaurus* and *Broiliellus* have the otic notch open behind; in *Algeinosaurus* the skull is unknown. *Aspidosaurus* has typically a single dorsal shield for each vertebra, firmly co-ossified to the expanded spine of the vertebra, the shields are roof-shaped and narrow transversely. *Algeinosaurus* has imbricated shields like those of *Aspidosaurus*, narrow and shallowly V-shaped, but free from the broadly expanded neural spines. It is possible that this freedom of the shields is due to age, for I am convinced that the shields in all these forms are of dermal origin. Until the skull of *Algeinosaurus* is discovered its precise relations to the other genera cannot be determined. I am convinced that it is nearly related to *Aspidosaurus*, but believe that it is a distinct genus. It will at once be distinguished from the present genus by the narrow, shallowly V-shaped, imbricated shields.

Aspidosaurus glascocki Case can only be provisionally located in this group. Its dorsal shields seem to be real expansions of the spines, meeting each other closely, but not imbricated. Nor can *A. crucifer* and *A. apicalis* be located here. I am confident that all these forms belong in an entirely distinct group, possibly the Zatrachydidae.

That all the forms discussed above show a genetic relationship there can be no doubt. Just what value the differential characters present, however, is a question. If we give to *Dissorophus* and

Aspidosaurus family rank it will be necessary to erect a larger group to comprise them all. I would rather place them all in the family Dissorophidae, in two subfamilies, the *Dissorophinae* and *Aspidosaurinae*.

Family **Dissorophidae**

Temnospondyl amphibians of small size, provided with dorsal osseous shields. Skull broad, depressed, more or less rugose, without mucous canals. Lacrimal entering orbit. Probably orbital ossifications in all. Otic notch greatly developed, extending far toward the orbit. Palate with slender parasphenoid; in front at least covered with chagrin-like teeth; two enlarged teeth only. Occipital condyles separated. Cleithrum large; clavicles and interclavicle small, not sculptured. Sacrum with two vertebrae (in all?); pelvis fully ossified, platelike. Femur with high, thin adductor crest. Feet fully ossified, short and rather broad. No ventral armature.

Subfamily DISSOROPHINAE

Otic notch closed posteriorly by the union of tabulare with quadrate below. Each vertebra with two dorsal shields, the under one either an expansion of the spine or a dermal ossification and smooth, the intercalated external shields sculptured.

Genus *Dissorophus*

Shields covering nearly the whole of the dorsum, the first one of large size.

Genus *Cacops*

Shields narrow, the first one small.

Subfamily ASPIDOSAURINAE

Each vertebra covered by a single, sculptured shield. Otic notch open behind. Ribs with uncinate process.

Genus *Aspidosaurus*

Spines greatly expanded above, with shields not much wider than vertebrae, and imbricated; more or less V-shaped. Orbits more posterior.

Genus *Algeinosaurus*

Like *Aspidosaurus* but the shields not coossified with spine.

Genus *Broiliellus*

Shields much broader than the vertebrae, not imbricated and not V-shaped; free from slender neural spines; skull spinose.

Dissorophus multicinctus Cope. Texas.
Cacops aspidophorus Williston. Texas.
Aspidosaurus chiton Broili. Texas.
Aspidosaurus novomexicanus Williston. New Mexico.
Algeinosaurus aphthitos Case. Texas.
Broiliellus texensis Williston. Texas.
Broiliellus peltatus Williston. Texas.

RESTORATIONS OF SOME AMERICAN PERMOCARBONIFEROUS AMPHIBIANS AND REPTILES

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University of Chicago

(WITH ILLUSTRATIONS BY THE AUTHOR)

The drawings illustrating the present paper were made in the hopes thereby of learning more concerning the animals as living organisms. Depending exclusively upon dried and petrified bones, the paleontologist is apt to forget that his fossils were once parts of living, active beings. Nearly all the restorations are based upon practically complete skeletons preserved in the museums of the University of Chicago or Yale University, technical descriptions of which have been published in various places during the past few years. Their living restorations, except that of *Eryops*, are here attempted for the first time. I will not attempt to give any technical details of their structure here; my only desire is to place before the general student of geology something of what I see, after years of study of the fauna, in some of the animals that lived in Texas and New Mexico during the closing times of the Pennsylvanian and the early times of the Permian.

The land vertebrate fauna of those times in America must have been very rich. More than forty distinct genera of amphibians and reptiles are represented in the collections of the University of Chicago, and the remains of at least a dozen more are preserved in the American Museum and at Yale University. It is the oldest fauna of reptiles known in the world, and by far the most comprehensive of the older amphibians known. The animals of the South African Karoo system are nearly all of later age, Upper Permian as distinguished from Lower Permian and Carboniferous, and they were, for the most part, more highly specialized and less primitive.

And the light these animals of the American Permocarboniferous have thrown upon the evolution of the higher vertebrates is very great, though there is very much more to learn. The primitive

FIG. 1.—A permocarboniferous landscape, with two figures of *Eryops* upon the land, each of about seven feet in length, and *Limnoscelis*, a cotylosaur of the same length, in the water.

structure of the skull in air-breathing animals, in part at least, of the mandibles, shoulder and pelvic girdles, wrist, ankle, and digits has been determined almost exclusively from these forms.

Three very distinct groups or orders of amphibians are known from these deposits, including more than twenty known genera. The first of these groups is represented by small animals of the water which must have existed in enormous numbers. There are places in Texas where the nodules containing their remains, usually nearly complete skeletons, may be obtained literally by the wagon-load. They resembled so closely in shape, and doubtless also in habits, the living *Amphiuma means* of the southern states, that a picture of that creature will almost serve for a restoration of this, which is known as *Lysorophus*. Most interesting is the fact that not only did *Lysorophus* resemble *Amphiuma* in size, shape, and habits, but it seems to be actually related to it, being the first representative known of the modern salamander type, not again known in geological history till the beginning of Cretaceous time.

A second group of very remarkable aquatic amphibians, whose relationships are still in doubt, is represented by *Diplocaulus*, a creature which reached a length of about three feet, having an extraordinary arrow-shaped head, and tiny, feebly ossified limbs of no terrestrial and little aquatic use. It, too, was a purely aquatic animal, whose remains are often found associated with those of the early sharks. A restoration of the skeleton of *Diplocaulus* will shortly be published in this *Journal* by Mr. Douthitt of the University of Chicago.

The third and most important order of all our Permocarboniferous amphibians is that known as the Temnospondyli, stegocephalians especially characterized by the divided condition of the vertebrae. They varied greatly in size, and doubtless also in habits, though none known were of upland habit. The most famous of these is *Eryops*, shown in Fig. 1 in what I have tried to represent as a characteristic landscape of the period in which they lived. It was an amphibian which reached a length of perhaps eight feet, and had a relatively large, broad, and flat head, no neck, a thickset body, and short, broad, probably webbed feet. The length of its tail is still in dispute, as may be inferred from

my restorations of the creature with that part of the body hidden in the water or under the ferns. Its skin was doubtless bare, and its tail more or less flattened for use in the water, like that of a gigantic salamander, its nearest living modern relative.

There can be no doubt that the creature was amphibious, though probably not strictly aquatic in habit, like *Trimerorhachis*,

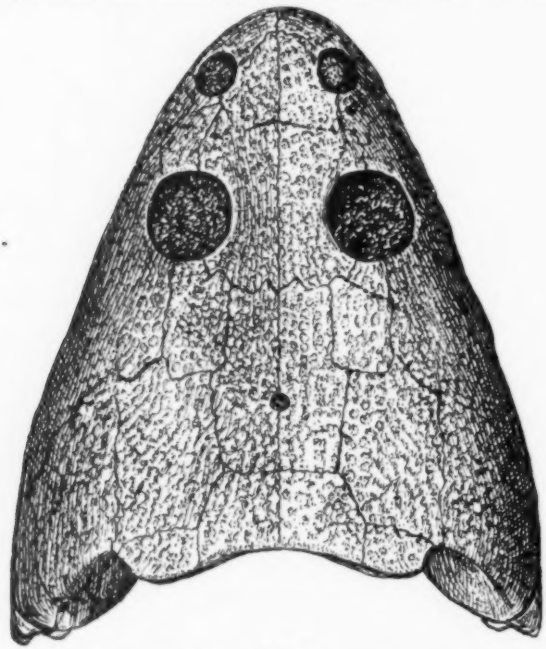

FIG. 2.—Skull of *Trimerorhachis insignis*, an aquatic amphibian about three feet in length.

remains of which are sometimes found in bone beds in great numbers. This animal, of which a restoration will be given in a future number of this *Journal*, had a more elongate and flattened head with the eyes far in front, and with almost vestigial limbs, as has *Diplocaulus*, which is often found associated with it.

Another animal of this order, which must be placed in a family all its own, the Trematopsidae, is shown in Fig. 3, as based upon

the only known specimen, preserved in the University of Chicago collections, consisting of a skull in connection with body and limb bones, except the front digits, and an imperfect tail. Its restoration, therefore, is subject to minor corrections when additional specimens are found. It was more of a terrestrial animal than any other known amphibian from this fauna, though it cannot

FIG. 3.—*Trematops milleri*, a stegocephalian about three feet long. From Texas

be called an upland animal, and doubtless it, too, could swim well. This creature was about two feet in length and has a relatively very large skull, fully two-thirds the length of its body to the tail. Its teeth also were more powerful than in other forms, though of the same general character. It is peculiar in showing an orifice in the skull for a facial gland, like that found in some modern amphibians.

A fourth and very peculiar type of the temnospondylous

amphibians is represented in the restoration of *Cacops* (Fig. 4), as based upon a marvelously complete skeleton, one of a dozen or more found associated with as many more of *Varanosaurus* and *Casea*, shown in Figs. 9 and 10. This animal, twenty inches in length, is one of a group of armored amphibians, very appositely called by Cope "batrachian armadillos," of which four or five genera are known, nearly all of the animals of approximately the same size. As suggested by Cope's name, they are all peculiarly characterized by a carapace of bony plates over the back; in some almost completely covering it, in others like *Cacops*, forming only a narrow row along the middle. In some of these has been found a peculiar bony plate in the orbits which could only have been used as a protection for the eyeball, possibly an ossification of the nictitating

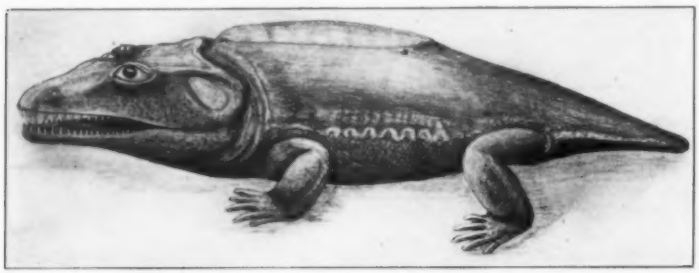

FIG. 4.—*Cacops aspidephorus*, a stegocephalian amphibian twenty inches in length. From Texas.

membrane. And one genus has the head covered with small, spiny excrescences. The ear, too, was conspicuously large, completely surrounded by bone in some, as shown. These amphibians, like most of the other small ones, must have been chiefly insectivorous, or invertebrate-feeding in habit, though the presence of stout teeth on the palate suggests that any seizable living prey was acceptable as food. They were all probably lowland animals, though *Trematops* may have lived more in the forests. *Eryops*, the largest known, has a skull sometimes nearly two feet in length; other small forms associated with it have skulls no larger than one's thumb nail. Doubtless the lowlands in the vicinity of water in late Pennsylvanian and early Permian times swarmed with these creatures and with cotylosaurian reptiles of similar form and habits.

Varied as were the amphibians, they were not nearly so numerous or so diverse in habit and structure as were the contemporary reptiles. While it is comparatively easy to classify the amphibians, the problems which the reptiles present are vastly greater. Hitherto they have been generally classed in two main groups or orders, the Cotylosauria and Pelycosauria, but the many discoveries of recent years have broken all boundaries and opened up most complicated problems of relationships, problems which will probably not be wholly solved in many years to come. It may be twenty-five years hence before we shall have a tolerably good bird's-eye view of the complete fauna. Especially are the smaller animals, those very difficult to collect and to study, for the most part yet awaiting laborious research.

FIG. 5.—*Diasparactus xenos*, a cotylosaur reptile of about seven feet in length. From New Mexico.

But there are about one dozen of these reptiles of which we know nearly all that we may ever hope to know, forms of which complete or nearly complete skeletons have been assembled and mounted. And it is of some of these that I have attempted restorations, and will briefly discuss here.

The order Cotylosauria, whose ultimate distinctions from other reptiles consist solely of the roofed-over skull, without holes in the sides behind, and a short neck, comprises a large group of the most primitive reptiles that we know. All that are known have practically no neck, short and stout limbs, a rather thick-set body, and for the most part not very long tails. They belong to three or four groups, that have been called suborders, and six or more strongly differentiated families. The first of these is represented by *Diasparactus* (Fig. 5), so nearly related to *Diadectes* that one restoration will do for both. It is a reptile of seven or more feet in

length, with short, stout legs, not very long tail, and with the head short and high, provided with crushing teeth behind and conical teeth in front. It has an enormous parietal opening in the skull, possibly suggesting a functional "pineal eye." These animals were at first thought to be burrowing in habit, because of the nature of their limbs; but burrowing would have been impossible, since by no possibility could the creatures have reached far enough forward to dig a hole for the head to enter. Nor do they show any decided aquatic characters, though doubtless they swam well.

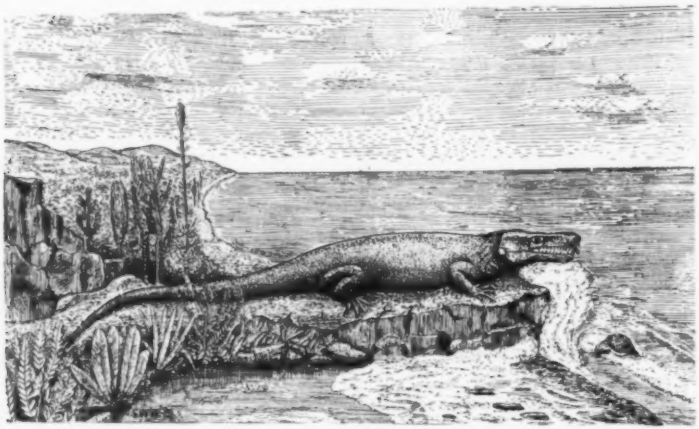

FIG. 6.—*Limnoscelis paludis*, a cotylosaur reptile, seven feet in length. From New Mexico.

Like the amphibians and most other cotylosaurs and some of the pelycosaurs, they were lowland or littoral creatures, living in and about the old lagoons and lakes.

The next type, the restoration of which is based upon a marvelously complete skeleton in the Yale Museum from New Mexico, is shown in Fig. 6, as also in part in Fig. 1. It had a much longer tail, and a more elongated and more powerful skull, beaklike in front, armed with strong, conical teeth, the foremost of which in the upper jaws were elongated and curved, as in the next group. Doubtless this was also a lowland reptile, as I have suggested in its

name, *Limnoscelis paludis*, meaning marsh-footed reptile of the swamps. This reptile reached a length of seven feet, and evidently had food habits somewhat like those of the next group, though more distinctly carnivorous and rapacious.

The third group, which is composed of numerous known species, varying in length from less than one foot to more than three, is represented by *Labidosaurus* (Fig. 7). I am less certain of the precise details of this creature, since, aside from the skull, the skeletons of the Chicago collection have not been fully worked out. The restoration is based largely upon the figures of the mounted skeleton in the museum at Munich, aided by various nearly complete

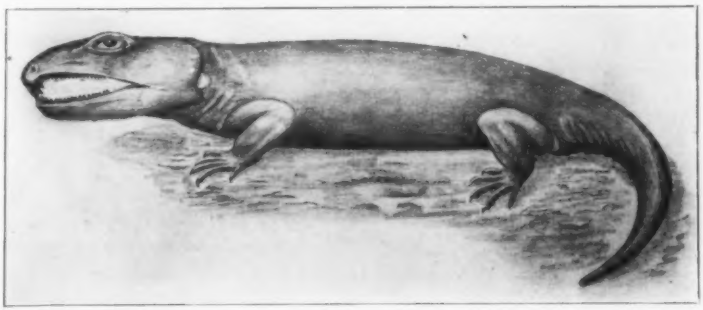

FIG. 7.—*Labidosaurus hamatus*, a cotylosaur reptile about four feet in length. From Texas.

skeletons of smaller forms. This group of cotylosaurs, the most highly specialized of our American forms, appears to have been of more distinctly terrestrial type than the others. Its limb bones are more slender, and the claws are sharp and curved, unlike those of other groups, where they are flattened terminal nails. Especially striking is the narrowed, beaklike skull in front, and the long, curved, sharp, and rakelike teeth, which suggest their food-habit, that of prodding in the mud and sand for soft-bodied invertebrates, or possibly for detaching limpet-like creatures from the rocks. The teeth of the jaws are arranged in two or more rows, used chiefly for crushing their food, not so much for cutting or tearing.

Still another family, the most lowly organized of all cotylosaurs

that are known, is represented by *Seymouria* (Fig. 8). It reached a length of not more than two feet, and had the shortest and broadest feet of all. Its skull is so nearly like that of the contemporary amphibians, especially that of some of the armadillo forms, not only in appearance, but also in actual structure, that close observation is necessary to distinguish them. The teeth are all slender and small, indicating insectivorous habits like those of the amphibians. Doubtless this too was a littoral inhabitant of more or less aquatic habit.

Still another group, one of the most peculiar of all, is unfortunately known only from the skull, of which the best specimens are

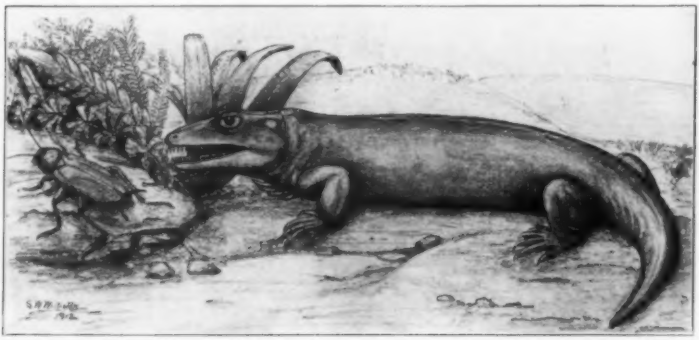

FIG. 8.—*Seymouria baylorensis*, a cotylosaur reptile about two feet in length. From Texas.

in the Chicago museum, and known as *Pantylus*. In size this animal was probably no longer than *Seymouria*. It is peculiar in having a broad, flat, and firm skull with the mouth filled everywhere, on jaws and palate, with low, stumpy teeth, suitable only for crushing shellfish.

Remarkable as is the diversity of structure and habit of these primitive cotylosaurs, that of the next group, commonly called the Pelycosauria, is vastly more so. The reptiles of this group or order, which I prefer to call the Theromorpha, after Cope, are all of a distinctly higher type, especially characterized by the lightened skull, which has one or more holes in its roof behind the eyes, and

by the longer neck and longer, more prehensile legs, and usually longer tails.

The best known of all these is *Dimetrodon*, various good restorations of which have been published. It was the largest of all the well-known animals of the American Permocarboniferous, especially characterized by its enormous crest, formed by the spines of its vertebrae, probably bound together by the skin. The skull was fiercely carnivorous in shape and in its teeth, and the largest species must have measured ten feet in length, though the length of the tail is not surely known. Our chief knowledge of the animal is due to Professor Case. It was the Bengal tiger of the fauna.

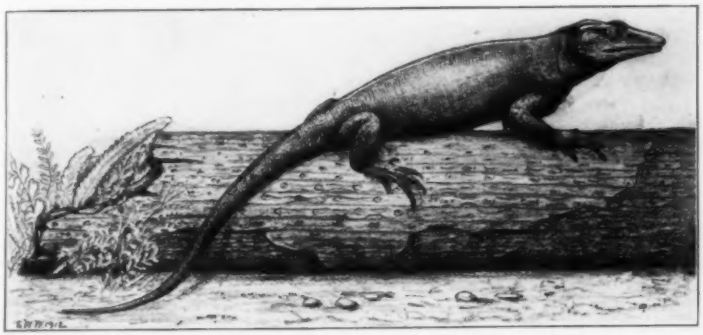

FIG. 9.—*Varanosaurus brevirostris*, a pelycosaurian reptile, forty-four inches long. From Texas.

Unfortunately the reptile whose restoration is most often seen in textbooks and popular works, as the most bizarre and the strangest of the fauna, is one whose real form and habits are very different from what they have been supposed to be. It has hitherto been called *Naosaurus* but its real name is *Edaphosaurus*, since only recently has its true skull, originally so named, been found connected with the vertebrae and with its true legs. A restoration of this strange animal will shortly be published by Professor Case.

Definitely and positively we know nearly every detail of the structure of the animal shown in Fig. 9, as *Varanosaurus*. The mounted skeleton of this reptile in the museum of the University

of Chicago is one of a dozen or more found associated in a bone deposit with as many more of *Cacops* and *Casea*. This reptile attained a length of nearly four feet. It had a rather slender body, a slender tail, and rather slender legs, and was marvelously lizard-like in form, and doubtless also in habits. Its teeth are slender and pointed, and were adapted only for the capture of insects and small animals. Its claws are sharp and its toes long. Without great climbing powers, *Varanosaurus* and its allies, of which there are several genera, were fleet-running reptiles, living in the forests,

FIG. 10.—*Casea broilii*, a pelycosaurian reptile forty-three inches in length. From Texas.

hiding under logs, and feeding upon the numerous cockroaches and other insects.

Associated with *Varanosaurus* in the same deposit of bones, were a number of skeletons of *Casea*, a restoration of which is shown in Fig. 10. It, too, was nearly four feet in length, but of very different habits from those of *Varanosaurus*. Its skull was remarkably short and thickset. It, too, has a very large pineal vacuity, which curiously seems often associated with herbivorous or malacophagous habits. The teeth were relatively few in number on the jaws, but the palate was completely covered with conical teeth. Its body

is extraordinarily broad and long, and of great stomach capacity; its shape is scarcely appreciable in the side view of the restoration. Its front legs were unusually powerful, and its sharp claws may have been used in burrowing. *Casea* was a relatively slow-moving, dry-land reptile.

Still more remarkable was the animal shown in Fig. 11, from New Mexico, a very perfect skeleton of which has recently been

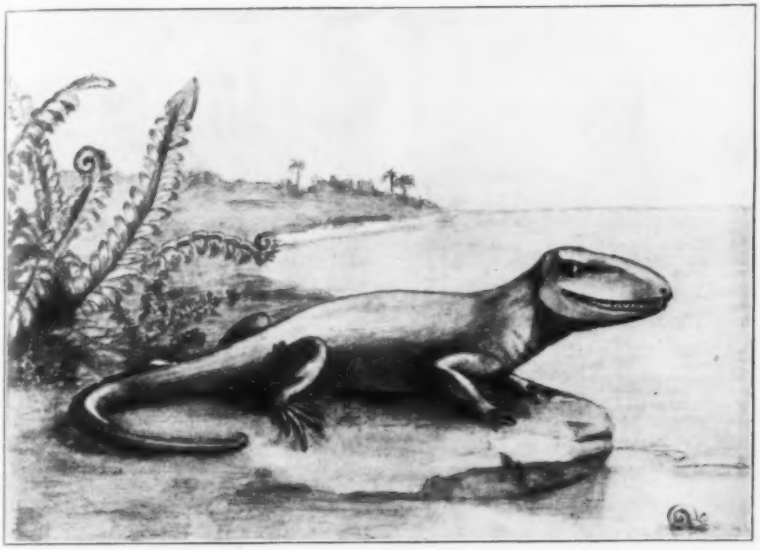

FIG. 11.—*Ophiacodon mirus*, a pelycosaur reptile about seven feet long. From New Mexico.

mounted in the University of Chicago museum. *Ophiacodon*, so named by the late Professor Marsh because of its slender, snake-like teeth, was fully seven feet in length, and is especially noteworthy because of its apparently enormous skull—apparently, though not really, since it is very narrow, and composed of delicate bones. The feet of *Ophiacodon* are the shortest and stoutest known among pelycosaurian reptiles, and its claws were blunt and nail-like, suggesting lowland or littoral habits, not unlike those of

most cotylosaurs. Its delicate and slender teeth could have been of no use in the capture of large prey; perhaps it preyed upon the numerous small amphibians and reptiles that swarmed in such regions. And doubtless it was more or less at home in the water, though not strictly an aquatic animal. From Texas, however, a very closely allied genus—*Theropleura*—is known to have more flattened and cutting teeth, suggesting more active carnivorous habits.

Finally, the last and most divergent group of all the known paleozoic reptiles of America is represented by a little, very slender, and slender-legged reptile of about one foot and a half in length, which I have called *Araeoscelis*. A description of this animal, giving nearly every detail in its structure, is now in preparation by the writer. Suffice it to say here that *Araeoscelis* is not only wonderfully lizard-like in form, but actually lizard-like in its structure, or as nearly lizard-like as one could expect in such ancient creatures; so lizard-like indeed that I firmly believe that it was actually closely akin to the ancestors of all our lizards and snakes, without a single character that would not be expected in the most primitive lizard. *Araeoscelis* was an exceedingly fleet, climbing and running reptile of the uplands, of purely terrestrial habits.

In conclusion I may add that, whatever may be the merits of these restorations as works of art, they have been drawn with most scrupulous accuracy so far as form and proportions are concerned, the musculature derived from the study of living reptiles. And, as I have said, they are all based upon practically complete skeletons; in a few only the precise length of the tail is yet unknown, or the front toes in *Trematops* and *Cacops*.

MECHANICS OF FORMATION OF ARCUATE MOUNTAINS

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SUMMARY

PART I

INTRODUCTION

The Alps the European type of the Asiatic mountain arc.—Studies of mountain structure have made use chiefly of profiles, or cross-sections, at right angles to the crests of the ranges. In recent years and to a relatively small extent only, longitudinal sections have also been figured in order to take account of the directions of pitching folds. In the geological map the plan of the region is of course represented, but chiefly with a view to fixing the areal distribution of the formations; and so far as known the discussion of the mechanics of the folding process has been restricted to the two dimensions included in the normal profile. While the reason for this may be in part the difficulty of representing more than two dimensions of space, it is no doubt due largely to a general belief that all significant elements in the problem can be properly set forth in the transverse section.

It was Eduard Suess who first clearly demonstrated the deep significance of the plan of arrangement of Asiatic or Euro-Asiatic mountain arcs. The Alps are to be regarded, as Suess has clearly shown, as an extension into Europe of the Asiatic mountain system, which includes also most of the ranges of southern and southeastern Europe. The name "Asiatic arcuate structure" or "Asiatic structure" is well chosen for the reason that this entire political division of Asia with the single exception of the peninsula of Hindustan, but including the entire group of island fringes as far out as the Bonin Islands and the Mariannes, is characterized throughout by the most pronounced of mountain arcs. Generally less typical, the same structure is represented upon the western continent by the sweeping arcs of Alaska, certain northern ranges of the Rocky Mountain system, and the Appalachians and West Indian ranges; while the only marked example upon the African continent is the Atlas range in the northwest.

In view of this extent and evident importance of the mountain arc, and its typical illustration in the Alps, no structural geologist can afford to remain in ignorance of at least the broad outlines of the Alpine problem. Whatever may be true of some other mountain districts that have been studied, here at least the plan as well as the vertical sections must be fully considered in the discussion of the mechanics of the folding process.

Conditions favorable for tectonic studies of the Alps.—No mountain region has excited so much interest in its structural problems as has the Alps. This is in part to be explained by its location in the very heart of Europe easily accessible to the geologists of every European nation, and in part by the scenic and hygienic qualities of the Swiss highland which have made it the playground not only of Europe but of the world as well. Its rugged features have been mapped in much detail and with praiseworthy accuracy, and the cartography of the country is the pride of every enlightened Swiss. Switzerland has, moreover, produced structural geologists who have ranked high among their fellows, and the complex problems of Alpine tectonics have gradually evolved from the early conception of Escher von der Linth to the brilliant theory of

Bertrand, later worked out by Schardt, Suess, Lugeon, Termier, Heim, and others.

It should not be forgotten that there are in the Alps some natural conditions which are favorable to the solution of its structural problems, and without which it seems likely that we should have advanced but slowly toward the goal. The rocks of which the Alps are composed are very largely sediments, which in a considerable portion of the area are uncrystalline and so richly fossiliferous that it has generally been possible to determine the place of each local bed within the vertical column. Almost as important in view of the peculiar character of the deformation, there is a horizontal differentiation of the beds from the northwest to the southeast which is recognized both in the petrographic character and in the fossils of the several formations. Thus it has been possible upon this basis to determine in some measure the lateral as well as the vertical displacements of the beds.

To a small extent only and in relatively few of the significant localities have the beds been greatly altered through the intrusion of igneous masses; and the regional metamorphism has seldom been so great as completely to destroy the identity of formations. Sculptured by glaciers into a fretted upland, the sheer mountain walls of the Alps, bare as they are of vegetation, often reveal in wonderful perfection all the intricacies of their complex structure. Thus with all its complexity the great problems of Alpine structure appear to be soluble, and it is easy to see that if differences of opinion still exist, we are none the less slowly approaching the goal.

To all these natural advantages for study there are to be added the network of mountain railways which surpass anything of the kind to be found elsewhere, a wealth of good hostelries, even at high and not easily accessible points, the numerous refuges, and the fraternity of competent and hardy guides.

For some other regions, such for example as that of southwestern New England, no one of the above-mentioned natural conditions is realized, and there is therefore good ground for believing that the problems of structure are in consequence practically insoluble. It is the author's belief, based upon many

years of study in the region, that though in certain favored districts maps and sections revealing internal structure may be prepared, for the larger portion of the region the most that can be expected is to derive a general notion from the study of the key localities.

The blanketing series of slices which make up the Alps.—It is not our primary purpose to present in detail at this time the modern Swiss interpretation of Alpine structure, or the objections which have been raised against it. Such an outline, important as it is for American students, who are likely to be bewildered by the many new terms, particularly when these terms are found in the original German and French sources, must be deferred until after the mechanics of the process has been considered. It is perhaps sufficient to allude here to the fact that the conception of series of blanketing slices (*Decken* or *nappes de recouvrement*), which originated in the mind of Bertrand in 1884,[1] was worked out independently and applied by Schardt in 1890–93 in the Voralpzone, and again by Lugeon in 1896, has now overcome all opposition in Switzerland, and, following its adoption by Heim himself in 1903, it has been the accepted doctrine of all Swiss workers without exception.

The story of the gradual acceptance of this theory reads like a romance and probably has no parallel in the history of geology. When the idea was first suggested by Bertrand upon the basis of his studies of the coal basin of northern France, no one seems to have taken the theory seriously as it applied to the Alps, since its author had never studied that region upon the ground. When nine years later Schardt was independently forced to similar conclusions in order to explain the structure within the area between the lakes of Geneva and Thun, he was vigorously opposed, by Lugeon among others. Hardly three years later Lugeon had been forced by his own studies to accept the new doctrine, and he is now its most prominent champion. Heim himself, whose name for almost a generation had been identified with the earlier theory of the double fold, accepted the new theory in 1903, and thereafter

[1] Marcel Bertrand, "Rapports de structure des Alpes de Glaris et du bassin houiller du Nord," *Bull. soc. géol. de France* (3), XII (1884) 318–30, Pl. 11.

it became standard doctrine throughout Switzerland. From Alpine countries outside Switzerland there have come examples of prominent structural geologists long identified with Alpine studies who first fought and later defended the Bertrand-Schardt conception of Alpine structure.

If a personal incident may be permitted, the writer's own experience has not been greatly different. In the summer of 1912 he entered the central Alps with the paper of Willis[1] in hand,

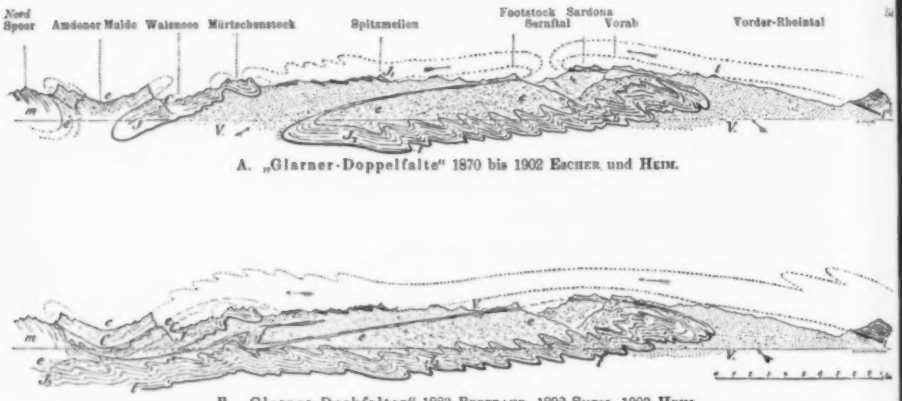


FIG. 1.—The Glarus folds and thrusts upon (*A*) Escher's conception of the double fold, and (*B*) Bertrand's view of overfolding and overthrusting (after Heim).

much impressed by the simplicity and the ingenuity of its conception; but after devoting the greater part of the season to examination of critical districts and to a study of sections across the central Alps, he became convinced of its insufficiency and of the general correctness of the now accepted Swiss view. There can be little doubt that this view is steadily gaining ground among those structural geologists who have given their attention to the subject.

Necessity for considering the mechanics of formation of arcuate mountains.—Though it be true that the theory of "overfolding and

[1] Bailey Willis, "Report on an Investigation of the Geological Structure of the Alps," *Smithson. Misc. Coll.*, LVI, No. 31 (1912), 1–13.

overthrusting" as an explanation of Alpine structure is steadily gaining ground, it is none the less a fact that there is much criticism of the mechanics of the processes which have been invoked, and the writer believes that this criticism is well founded. Swiss geologists profess to regard this phase of the subject as of slight importance; but so long as it is necessary to reconstruct from incomplete surface indications folds which are in part concealed below the surface, the contention of these geologists can hardly be admitted to be justified. No better illustration could be offered than contrasting the "double fold" and the "blanketing nappes" theories as applied to the classical district of the Glarus (Fig. 1). Both theories involve complex structures which have never yet been found complete in any region, and discrimination between them must of necessity depend in some measure upon the possibility of accounting for their formation as a result of conceivable stress-strain conditions during a profound deformation of the region. In order to throw light upon their origin, all that is known of the mechanics involved in the folding process should be brought to bear, with due consideration of the fact that the Alps furnish a perfect illustration of the Asiatic type of mountain arc.

THE FOLDING PROCESS STUDIED IN THE PLAN—ARCUATE STRUCTURE

Areal and morphological characteristics of Asiatic ranges.—Study of a modern map of Asia upon which the relief has been indicated brings out some quite remarkable facts of distribution of the mountain ranges (Fig. 2). These facts might be stated in somewhat categorical form as follows:

1. The ranges are arcs which present their convex sides to the oceanic areas.

2. The arcs taken together in part inclose a relatively rigid mass of ancient rocks which from earliest geological times has been a land area and has become known to geologists as the Angara coign or shield.

3. The inner arcs of the series are the older and simpler in form and have the largest radius of curvature.

4. The intermediate and outer groups of arcs of the imperfectly concentric series are of later date and consist of festoons, or spring from a number of cuspate areas. This arrangement is described as "linking" or "syntaxis."

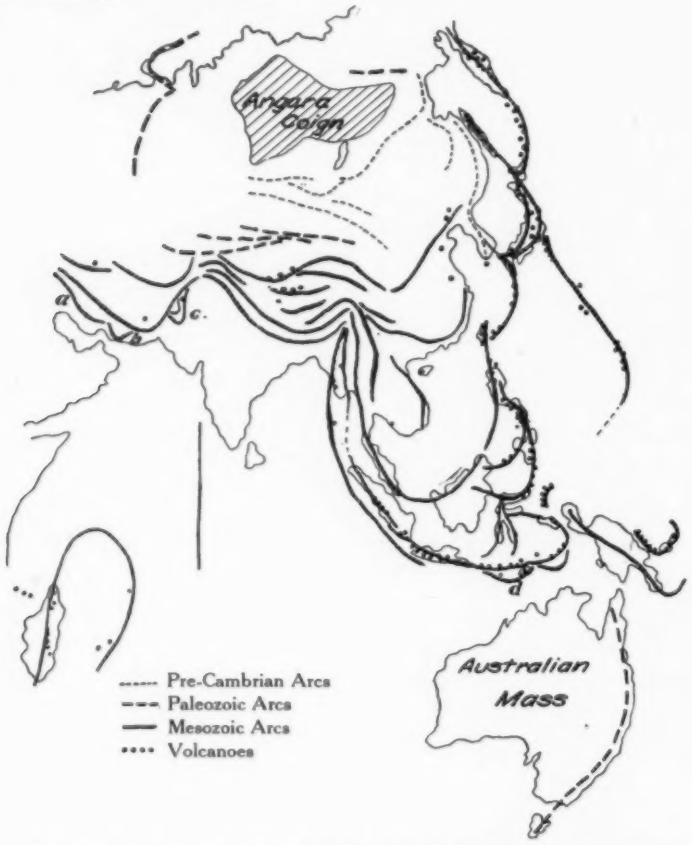


FIG. 2.—Sketch map of Asia to bring out the plan of the principal mountain ranges with indications of the partially submerged chains.

5. Several arcs of different radii in some cases spring from the same pair of linking areas which thus become centers of "virgation." The nearly parallel ranges near where they are linked are sometimes referred to as *coulisses* (Fig. 3).

6. Within the geologically recent peninsula which comprised the present Malayan peninsula, Indo-China and Malaysia, the arcs are developed in relatively much narrower and deeper festoons than elsewhere, thus giving the impression of having been subjected to strong lateral compression.

7. Locally and upon the outermost series of arcs, particularly, are superimposed arcs of smaller order of magnitude arranged after the manner of a scalloped border (Sewestan, Timor, etc., Fig. 2, *a*, *b*, *c*, *d*).

8. The outer group of arcs is paralleled by near-lying arcs of

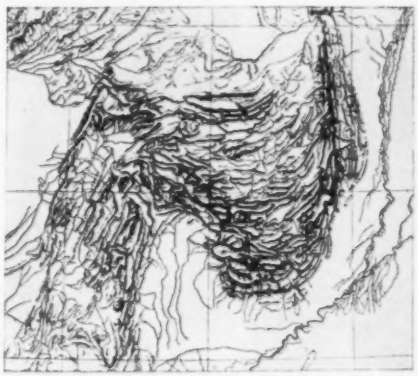


FIG. 3.—The multiple arc of Sewestan, British India (after de Saint Martin and Schrader).

volcanoes generally upon the concave margin, and these vents are characterized by unusually strong activity (see Figs. 2, 4, and 5).

9. Upon the convex margin of the outer series of arcs particularly lie "fore-deeps" (Fig. 5).

10. The outer series of arcs is characterized by extraordinary seismic activity (Fig. 6).

11. The outer arcs lying between the ancient Angara land-mass and the Pacific Ocean are to a marked degree asymmetric, each succeeding arc in the series springing from the side of its neighbor (see Fig. 2).

Structural peculiarities of the arcs.—Of all mountain arcs of strongly marked Asiatic type, the Alps have been most carefully

studied with respect to tectonic structure. Speaking broadly and in the usual terms, this arc consists largely of a series of sediments folded into closed recumbent flexures with axial planes which incline (except where the crown has sunk) toward the interior of the arc, and which are further extensively "overthrust" and "overridden"

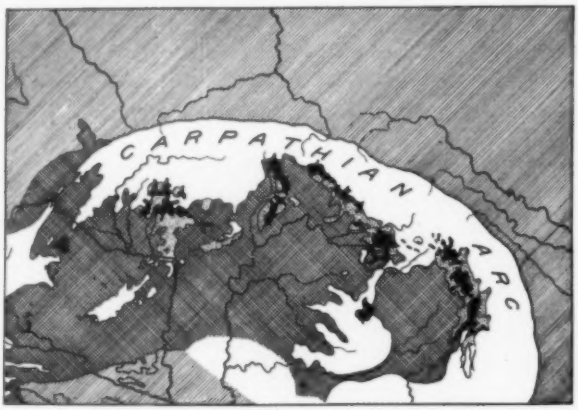


FIG. 4.—Arc of the Carpathians with volcanoes ranged upon the concave margin (after de Martonne).

FIG. 5.—Sketch map to show the relation of fore-deeps and arcs of volcanoes to Asiatic arcs.

in the same sense. Such knowledge as we have of the arcs of Asia, now fortunately assembled and analyzed by Suess, indicates that in a very general way close recumbent folding and "overthrusting" is characteristic of them, and that the dip of the axial planes and the "thrusts" takes the same direction toward the interior of the arc. Quite recently a somewhat comprehensive tectonic study

of the Timor arc (*d*, Fig. 2) by Molengraaff[1] has shown a quite remarkable parallel with the *Deckenbau* of the Alps. Examples of "overthrusting" in extra-Asiatic arcs seem to be augmenting as these are studied with greater thoroughness.[2]

Centrifugal versus centripetal distribution of the active forces which produce mountain arcs.—In a broad way the great Asiatic mountain arcs no doubt owe their location to the presence of lenses of sediments laid down in former epicontinental seas along the borders of the growing continent of Angara. This fact alone would account for their essentially annular arrangement about the ancient coign of the continent as a center. It does not, however, explain the formation of the flexures or the places of location of the individual mountain arcs. There seems to be no difference of opinion that in some way the arcs are due to a system of tangential stresses which operated within the earth's outer shell. Suess has assumed that the system of stresses which produced the Asiatic arcs acted from *within the arcs outward*, or, in other words, was centrifugal, the more rigid and

FIG. 6.—Outline map of the Asiatic continent and neighboring archipelagoes to show (in black) the seismic zones. Note the close correspondence with the outer series of mountain arcs (Fig. 2) and with the zones of volcanoes (after de Montessus de Ballore).

[1] Paper read at the Twelfth International Geological Congress in Toronto, August, 1913.

[2] See A. Hamberg, "Die schwedische Hochgebirgsfrage und die Häufigkeit der Überschiebungen," *Geol. Rundsch.*, III (1912), 226–35; also Bailey Willis, "Überschiebungen in den Vereinigten Staaten von Nordamerika," *C.R. IX Cong. Géol. Intern.*, Wien, 1903 (1904), 531, 539–40.

hence resistant masses lying outside;[1] a view which has been rather generally accepted, it would seem, and which is followed, among others, by Arldt.[2]

To accepting this conception there is an insuperable objection from the standpoint of mechanics. The necessary reduction in area of the strata through duplication by folding and "overthrusting" is certainly great, and if this duplicated and often reduplicated expanse of strata has come from within the area inclosed by the arc, one of two consequences must have followed. Either a hiatus must have developed near the center of the area,

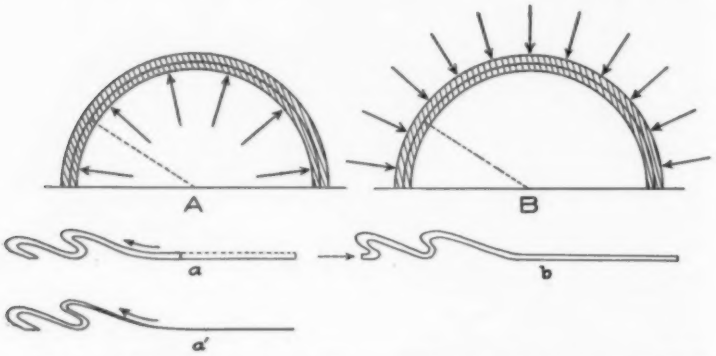


FIG. 7.—Diagrams to contrast the conceptions of centrifugally distributed (*A*) and centripetally arranged (*B*) forces in the production of mountain arcs. The lower figures are enlarged sections along the dotted lines, and the arrows in all cases give the directions of the (assumed) active forces.

or else the strata must have become greatly attenuated, an effect which should be increasingly apparent in the upper and later folds of the series and throughout in the upper limbs more than in the lower (Fig. 7, *Aaa'*). If, upon the other hand, the arcs are to be explained as a result of centripetally distributed forces coming from outside the area inclosed by the arc, these difficulties are not encountered for the reason that contraction of surface of large portions of the earth's outer shell may be assumed to supply the

[1] Ed. Suess, *Antlitz der Erde*, III, 1–2.

[2] Th. Arldt, *Die Entwicklung der Kontinente und ihrer Lebewelt*, Leipzig, 1907.

strata which are duplicated and reduplicated in the recumbent and "overthrust" folds (Fig. 7, *Bb*).

A centrifugal system of active forces implies that a mass relatively rigid and resistant with respect to that within surrounds the arc. Centripetally distributed thrusts, upon the other hand, imply that the area within the arc is relatively the more rigid and less capable of lateral migration.

Deductions concerning the relative age of Asiatic arcs.—If now we apply this criterion of distribution of thrusts, not to individual arcs alone, but to the Asiatic series as a whole, the centrifugal system of thrusts meets with a no less serious additional difficulty; for it would in this case be necessary to assume that the outer arcs were the first formed and the inner arcs the latest. Upon the other hand, a centripetal arrangement of active forces requires that the reverse should be true. That such is the case appears to be supported by at least four important considerations: namely, (1) the plan of distribution; (2) the position of the more rigid mass; (3) the known geological age of the ranges; and (4) the present locus of seismic and volcanic activity.

That the outer arcs of the system are, so to speak, laid on or applied to the inner ones is apparent from observation of the outline map (Fig. 2). More especially is this the case for the smaller arcs attached to the eastern wing of the great Burman Malaysian series and its extension to the north; as it is also for the arcs of Seyestan (Fig. 2, *c*) and Timor (Fig. 2, *g*).

As regards the position of the relatively more rigid area, we know that the Angara platform is an ancient land-mass which has been undisturbed since the Cambrian, whereas outside of the area of the arcs, if we except the remnant of the Gondwana continent in Hindustan and the separated mass of Australia, we encounter only the depressed oceanic basins.

The inner series of arcs, less clearly marked out morphologically as a result of long-continued erosion, we find to be of pre-Cambrian and Permo-Carboniferous age, though accompanied in some instances by later foldings. Farther out we encounter the great Tertiary welts of the Himalaya, Hindu-Kush, and their extensions which have been so recently elevated that erosive

processes have not yet succeeded in reducing their excessive relief. Still farther outward and upon the margins of the system, we have mountains which may more properly be described as in the making, with all the accompaniments of strong earthquake and violent volcanic eruption.

The ocean basins the loci of dispersion of tangential thrusts.—To this conclusion we are led by the considerations of the last section.[1] To the tectonic argument modern seismology has made a contribution of the first importance. Until within a quarter of a century it had been the custom to regard the continents as the regions of the most active geological movement upon our planet—a striking illustration of the assumed dominance of phenomena near at hand and often observed in fixing the basis of judgment. Yet a moment's thought shows us that the floors of the oceans are masked beneath a mobile cover which must effectively damp all disturbances that emanate from them. Now that a means has been discovered for seismically exploring this vast area and subjecting its movements to measurement, we have been surprised to learn that its mass movements are, area for area, vastly greater than those of that portion of the lithosphere which projects above the seas.

If we except the immediate vicinity of the continents, there is evidence that as a whole the movements upon the ocean floor are downward toward the earth's center, and hence the greatest reduction in superficies is there today in progress. Of this the evidence is twofold. By far the greatest of all macroseisms proceed from the deeper portions of the ocean floor, and we may draw the conclusion that if the mass movements were not in general downward rather than upward, these areas could hardly remain the deeps. On the other hand, except in the neighborhood of great deltas, most mountain shores of the continents are today rising. This is eminently true of that remarkable fringe of island arcs which lie to the eastward of the Asiatic continent, a fact amply demonstrated by the elevated shore lines and high coral reefs. The amounts of elevation are here further in direct proportion to

[1] See also T. C. Chamberlin and R. D. Salisbury, *Geology*, I, 517–18, 520–21.

the breadth of the fringes.[1] The narrow Liu Kiu and Kurile island arcs—mere lines of volcanic summits with no visible cordillera—show evidence of relatively slight elevation only, and these lie opposite the great sinking deltas of the Hoang and Yangtse in the one case and the Amur in the other. Still farther out toward the center of the Pacific, the Bonin group indicates some islands rising, others sinking, and still others rising after a depression—the group as a whole without as yet very strong indications of general uplift.

There is still the further argument that throughout the area of the coral seas, as was first pointed out by Charles Darwin and James D. Dana, working independently, the ocean floor has long been sinking, since in no other way can atolls be adequately accounted for.[2]

Any general movement of the ocean floors in the direction of the earth's center which is in excess of movement in the same direction in the continental areas must be accompanied by an out-thrusting against the continental margins such as would be required to explain the formation of mountain arcs uniformly facing the sea. That such thrusts are in reality carried out to the continents from the oceanic areas and cause landward migration of strata is also necessary to account for the fact that the elevation of mountains is not accompanied by tensional phenomena such as the gaping of fissures, etc. Mountain growth accompanied by strong earthquakes reveals in the behavior of rails, pipes, bridges, etc., the fact that not expansion but contraction of the surface has resulted from the movement.[3] The so-called block or *Schollen* theory of formation of mountains, amply demonstrated by observation in many regions, has had to contend with the supposed theoretical difficulty that opening of fissures by tension should result.[4]

[1] *Bull. Geol. Soc. Am.*, XVIII, (1907) 233–50, Pl. 5.

[2] The ingenious rival theories of Sir John Murray and other biologists fail utterly to explain certain necessary geological consequences. Professor Davis has utilized the Dana centennial to recall Dana's decisive discussion upon this point and to strengthen it by his own arguments.

[3] "A Study of the Damage to Bridges during Earthquakes," *Jour. Geol.*, XVI (1908), 636–53.

[4] *Proc. Am. Phil. Soc.*, XLVII (1909), 27–29.

So soon as we attempt to estimate the lateral migration of a point at the shore due to any given sinking of a definite arc upon the ocean floor, we find that the measure of the movement is probably insufficient to account for the duplication of strata in mountain folds. The landward migration corresponding to a uniform descent to a depth of one mile within an arc a thousand miles in width, if divided equally between the coasts on either hand, would amount to only about $1\frac{1}{2}$ miles, or, if concentrated upon one coast, to double that amount.[1] Account is to be taken, however, of a concomitant change in volume due to a relative elevation of isogeotherms into the descending sector of shell. Sedimentary rocks expand upon the average about $\frac{1}{190}\frac{1}{192}$ for each degree Fahrenheit, or 2.75 feet per mile per hundred degrees.[2] An arc of a thousand miles should thus be extended, from elevation of temperature in a uniform descent of one mile, a distance of between 1,985 and 2,770 feet, according to what figure is taken for the geothermic gradient. If this effect be added to that which is due to shortening of the arc, the expansion of the strata in the arc would be about $3\frac{1}{2}$ miles per thousand miles of arc. This figure, though somewhat small, is probably of the right order of magnitude to account for the duplicating of strata in mountain ranges.

If now we consider the possible effect of a disappearance through depression of the Gondwana continent upon outthrust toward the continent of Asia, we are warranted in assuming for Gondwana Land a fairly high level, for the reason that even within the tropics there was extensive glaciation. The average depth of the Indian Ocean may be taken as 4,200 meters, and the average descent of some three miles over an arc of 5,000 miles is not improbable. If this outthrust caused landward migration of strata upon the Asiatic shore only, the outthrust northward would correspond to a displacement of about 52 miles. This is, however, a maximum figure, and

[1] J. D. Dana estimated that within an arc corresponding to a quarter of the entire circumference of the globe, a uniform descent of 8 miles would cause a lateral displacement of 12 miles ("On the Origin of Continents," *Am. Jour. Sci.* (2), III [1847], 97).

[2] T. Mellard Reade, *The Origin of Mountain Ranges*, London, 1886, pp. 109–12.

should be diminished by any folding upon the opposite end of the arc, by reduction in volume of the strata, by any closing-up of joint spaces, etc.

In this connection it should not be overlooked that when the stage of sliding has been reached in the process of folding, the surfaces of dislocation in nearly horizontal attitude so facilitate underriding of strata that this may follow contraction without the necessity of infall of the depressed areas.

Form of the arcs and their distribution an expression of the space relations of continental pedestal and ocean floor.—If we are to assume the ocean basins to be the great loci of dispersal of compressive tangential stresses within the earth's shell, as brought out in the last section, we should examine each one of the Asiatic series of arcs to note whether it correctly expresses what is known of the distribution of ocean and continent and of deepening or shallowing conditions in the former at the time of arc evolution. In pursuing this inquiry we note that the Permo-Carboniferous arcs to the southward of the Angara coign should have a general east-and-west trend in order to correspond to thrust from the Tethys Sea which at the time of their formation stretched in that direction over what is now southern Asia and separated Angara land from the great Gondwana continent to the south. To the eastward of the ancient coign the general trend of the arcs should not, however, differ greatly from that of the later arcs in the same vicinity or of the shore line of today.

The extension of the Angara continent southward over the Paleozoic Tethys, and the formation of the Indian Ocean by the breaking-up and partial sinking of the Gondwana continent previous to the folding of the early Tertiary period, is likewise in conformity with the greater accentuation of the curvature of the Tertiary welts across southern Asia. The growing peninsula which in Tertiary time connected the Malaysian archipelago to Asia was partially protected from southerly thrust by the mass of Australia, while being pinched between the eastern sea in the Indian Ocean and the vast Pacific. We may thus perhaps account for the elongation of the Burman-Malay arcs and their noteworthy lack of symmetry as well.

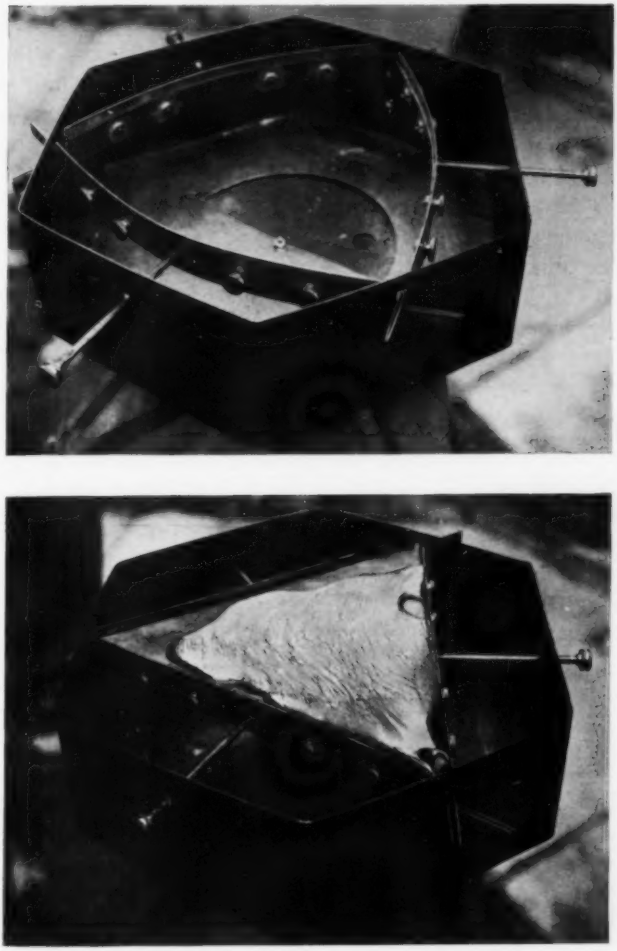
The great central remnant of Gondwana land which in Cretaceous time joined Madagascar to Hindustan, stretching across the central zone of the present Indian Ocean, persisted in large part through the early Tertiary and may account for the main subdivision of the Tertiary arcs to the north of Hindustan as well as the well-defined compressed arc which still exists in part submerged to the northward of Madagascar.[1]

In later Tertiary time the Malaysian extension of the continent grew to the southeastward and the union of the two great seas to form the present Indian Ocean increased the thrust from the southwest and opposed more strongly that from the Pacific. From the south-southeastward the shielding mass of Australia should reduce the thrust upon the front of this arc and so favor its lateral compression from the oceans on either side. The smaller marginal arcs ranged in series, such as we find in the Philippine archipelago, show in macroseisms continued depression of their fore-deeps, and this indicates that the growth of the arcs may continue at a rapid rate after new arcs (here the Bonin) have begun to form farther out toward the central area of the ocean.

THE FOLDING PROCESS STUDIED IN THE PLAN—EXPERIMENTS WITH CONTRACTING FILMS

An imitation of arcuate structure may be produced by allowing slightly plastic films on stretched rubber sheets to contract after being locally rigified. This is best accomplished by use of hot Canada balsam spread in thin layer upon a sheet of stretched rubber such as is in use for the manufacture of bellows. An apparatus designed for such experiments is represented in Fig. 8 and consists of a strong metal frame within which three brass springs are so related to each other as to outline in the plan a plane equilateral triangle when in unstrained condition. When this triangle is manipulated by simple rods of metal notched upon the lower side, the degree of expansion of the triangle may be varied and maintained for any desired length of time. The springs which

[1] This arc is outlined upon Madagascar and in the Farquahar, Amirante, Seychelles, and Coetivy islands, the Saya de Malha Bank, and the Cargados, Mauritius, and the Réunion islands (see Fig. 2, p. 78).



A

B

FIG. 8.—Apparatus for the simulation of mountain arcs through the contraction of locally rigified films of plastic material. *A*. View of frame with metal triangle in extended position. *B*. The same with sheet of rubber supporting a layer of Canada Balsam which was poured hot and when the rubber sheet was stretched, but was locally rigified and then forced to contract upon the relief of tension in the rubber.

compose the sides of the triangle are double and provided with clamp screws to permit of fastening the rubber sheet at its margins. When in use, the frame is placed upon a ring tripod, and since the frame is supplied with a window in its bottom, cold masses of metal of any desired shape may be introduced below and brought in contact with the under surface of the rubber sheet in order to induce local premature rigifaction of the cooling layer of balsam resting upon the sheet.

The principal difficulties encountered in carrying out the tests are due to the necessity of evaporating the balsam so that it will rapidly rigify in cooling and still be sufficiently fluid when poured upon the sheet to spread out into a thin layer. The evaporation can be accomplished upon a water bath, but a slightly higher temperature given it just before pouring is desirable. If the temperature is carried too high the surface of the rubber may be seriously affected.

The series of concentric arcs which appear in the balsam layer represented in Fig. 8 are due to the local rigifaction of a circular area near one side of the triangle but not centered upon a bisectrix, with the principal contraction of the sheet from the two sides opposite the convexity of the arc.

Reviews

Structural Geology. By C. K. Leith. New York: Henry Holt & Co., 1913. Pp. 169; figs. 68. $1.50.

The central feature of this admirable work is the interpretation of rock structures as expressions of dynamic processes, rather than descriptions simply. Students of geology are generally more or less familiar with the different kinds of rock structure, simply as such, but they are not so generally accustomed to interpret these structures as related parts of a record or of a process. In this work the author has adopted a philosophical mode of treatment by approaching rock structures from the point of view of the forces and processes which have produced them. The structural phenomena are aligned chiefly as the products of fracture or of flow.

As the book is relatively short, the author plunges at once into a critical discussion of rock fracture and rock flowage and of the controlling conditions which express themselves in one or the other of these two methods of deformation. Then in the light of the principles of rock fracture which have been developed, he takes up in detail the treatment of the leading rock structures resulting from this type of deformation. Of these, faults naturally receive the greatest attention, but a fair apportionment is given to joints, fracture cleavage, breccias, and autoclastics. Earthquakes, both as causes and effects of rock fracture, complete the first half of the book.

In the second half, under the heading of rock flowage, are treated in order flow cleavage, gneissic structure, and porphyritic textures developed by rock flowage. These lead to a digression on the identification of schists and gneisses, in which the stand is taken that with our present knowledge, field observations are likely to yield more satisfactory conclusions as to the igneous or sedimentary origin of given gneisses and schists than either mineral or chemical composition. Folds are treated as structures common to both the zone of fracture and the zone of flow, but folds developed in these two zones may be discriminated by the contrasts which they exhibit in a number of particulars.

Mountains and the other major units of structure each receive a brief but pointed consideration. Isostasy as an agency to explain these relief features is analyzed and then criticized on a number of

grounds. Dr. Leith states squarely that isostasy and rigidity in any high degree are mutually exclusive and as between the two he favors rigidity. The rigidity of the earth is a matter whose importance has been very generally passed over lightly, or carelessly swept aside by students of mountain building. But the brilliant determination of earth rigidity now in progress by Michelson, Gale, and Moulton firmly establishes the view favored by the author. The results seem indeed already to foreshadow that rigidity is the rock upon which not a few favorite theories are destined to be wrecked.

The average reader will perhaps be struck with the absence of numbered chapters. The framework of the book is really a skeleton outline—the familiar blackboard device of the systematic lecturer—with a few principal headings, under which are marshaled a graded series of subheadings. The relative importance and correlation of these are rendered easy by different styles of type. For systematic study as well as classroom presentation this method has its advantages.

The treatment is strong and judicial; the discussion closely woven and effective, and while conciseness and brevity were doubtless sought, they result in very concentrated nourishment. The reviewer is of the opinion that the average working geologist will wish that the book were about twice as long. The treatise is a distinctly valuable contribution. It has no equal in its field.

R. T. C.

The Devonian and Mississippian Formations of Northeastern Ohio. By CHARLES S. PROSSER. Geological Survey of Ohio, 4th Ser., Bulletin No. 15. Pp. ix+574, 33 plates. Columbus (1912), 1913.

The author devotes five chapters, or a major part of the bulletin, to a detailed description and discussion of the more important rock sections exposed in northeastern Ohio, together with observations on the fossils usually found associated therewith, and to a review of the literature bearing on the geology of that section of the state. This is followed by a chapter on correlation, and the bulletin concludes with the description and illustration of the major part of the Chagrin fauna, in which are included four new species and two new varieties.

The sections alone are a valuable addition to our knowledge of the geology of that region, as they bring out clearly the varying character of the rocks which have usually been classed together as a single forma-

tion. A great many of the sections and plates emphasize the importance of the erosional surface on which the Berea sandstone often rests.

The following classification of the rocks exposed in the region under discussion gives the formational relationships as used:

Pennsylvanian	Sharon conglomerate	
	Royalton formation	
	Sharpsville sandstone	
Mississippian	Orangeville formation	Brecksville shale
		Aurora sandstone
		Sunbury shale
	Berea grit	
	Bedford formation	
Devonian	Cleveland shale	
	Chagrin formation	

On the evidence of its fossil content, the author has definitely correlated the Chagrin formation with the Chemung of Western New York, and the Huron shale in general is regarded as the western stratigraphic equivalent of the Chagrin formation. The fact that the Cleveland shale thickens to the southwestward is observed to be due "largely to the downward encroachment of the black deposits upon the Chagrin" and to a similar "encroachment of the typical Cleveland black shales upon the lower deposits of the Bedford formation." To the eastward, however, the Cleveland shale is found to decrease in thickness and to be wanting in the sections near the Ohio-Pennsylvania line, possibly in all those east of the Grand River valley.

In the Bedford formation, the Euclid sandstone lentil near the base and the Sagamore sandstone lentil at a somewhat higher horizon are described. The disposition of the Bedford formation is not quite so clearly made but it apparently either thins out entirely before the Pennsylvania state line is reached or is represented by a part of the Venango sandstones and shales, possibly including the Riceville shale, of Pennsylvania. As evidence of its thinning out the finding of Chagrin fossils in deposits below but very near the base of the Berea sandstone is cited. "The results obtained in this bulletin seem to show conclusively that the Berea formation of Ohio is the western equivalent of the sandstone of western Crawford County, Pennsylvania, identified by Dr. White as the Corry sandstone and the subjacent Cussewago shales and Cussewago sandstone." The sections given for this eastern region show that the splitting up of the Berea sandstone begins at least as far west of the Pennsylvania state line as Windsor Mills, near the west line of Ashtabula County.

The most important change made in the classification, as formerly used, is the breaking up of the old Cuyahoga formation into the Orangeville formation, Sharpsville sandstone, and Royalton formation, while the Sunbury shale becomes merely a subdivision of the Orangeville. The two lower divisions of the Cuyahoga are considered to be the western extensions of the formations of the same names in western Pennsylvania, while the Royalton formation is apparently the Meadville, with perhaps also the Shenango, of the Pennsylvania classification.

This volume is by far the most important stratigraphic publication issued by the Geological Survey of Ohio in recent years. It deals with a part of the state which has been very much misunderstood by many of the former workers in that region and therefore misrepresented to the geological world. Undoubtedly the greatest importance of the bulletin lies in its bearing on the boundary line between the Devonian and Mississippian of Ohio, which is still a subject of much controversy. It appears that Dr. Prosser favors drawing this line at the base of the Berea sandstone, but he makes the statement that he "has not yet reached a positive conclusion concerning the age of this [Bedford] fauna," which is now used as marking the introduction of Mississippian sedimentation. The reader is therefore allowed to draw his own conclusions from the evidence presented.

C. R. S.

Geologische Diffusionen. Von RAPHAEL LIESEGANG. Dresden und Leipzig: Theodor Steinkopf.

The newer advances in mineralogy and petrology owe much to the work of the German chemists during the last quarter of a century. One of the most recent fields of investigation, which German workers have made peculiarly their own, is colloidal chemistry. The field is yet so new that geologists are only now beginning to realize the importance of its applications to their own science. At such a stage a book written from the point of view of the colloidal chemist is decidedly welcome. While it is today impossible for one man to be a specialist in two sciences, it is in the best interests of scientific progress that the applications of this branch of chemistry to geology be first made by an authority on colloids, rather than by a geologist. A study of the book before us is calculated to convince those who may be skeptical on this point.

The very special value of the book to the geologist lies in the detailed description of such experiments on the diffusion of colloids as may have

a bearing on geological processes. To a large extent the author has drawn on his own work, and has provided material which it would be very difficult, if not impossible, for the geologist to obtain elsewhere. Most important are the experiments on "rhythmic precipitation" or banded structure, which is formed, for instance, when silver nitrate diffuses through a gel containing potassium bichromate. The silver chromate forms in concentric bands separated by clear interspaces, at once suggestive of the ring structure of the agate.

In applying the results of the experiments to geological structure, the author displays—for a specialist in another science—a remarkably good knowledge of geological literature. Few economic geologists would be prepared to give such an important place to lateral secretion as the agency by which veins are filled, but many objections to the theory are met by reference to actual experiment. The chief value of the book lies in the application of "rhythmic precipitation" to agate structure, banded flints, eozoön, banded clay concretions, and "weathering rings." The treatment of alternating gold and pyrite layers in quartz from the same point of view will be subjected to question. The author has at least added another to the explanations which have been offered for the gold deposits of the Rand.

Without doubt the author has provided geologists with material which will be the means of opening up a new and fascinating field for investigation in the very near future.

R. C. WALLACE

Fosseis Devonianos do Paraná. By DR. JOHN M. CLARKE. "Monographias do Servico Geologico e Mineralogico do Brazil," Vol. I. Rio de Janeiro, 1913.

In his recent monograph on the Devonian faunas of the southern hemisphere Dr. Clarke has placed Brazil in the same position of honor in the southern continent that New York has always held in North America, as the holder of the standard Devonian column and geologic record of that time. The work in its philosophic treatment and broad learning, as well as in its perfection of illustration and text, is beyond all criticism.

The paleogeography of the Devonian is discussed thoroughly, and a map is given showing the distribution of land and water in that age, to express the relations of the faunas. This map shows the austral continent connecting South America with South Africa, some central

island masses in northern South America and central Africa, and the great boreal continent connecting North America with Eurasia. The austral faunas flourished on the northern strand of the austral continent, separated from the northern facies by the broad central ocean. The two types seem to have sprung from the same Silurian ancestors, to have diverged slightly in isolation under the influence of their environment, but to have developed along similar lines on account of "long-standing impulses in definite development which realize themselves notwithstanding conditions of geographic isolation." It would seem that we have here one of the most remarkable and definite cases of orthogenesis in the world's history.

There are in the fauna thirteen species of Trilobites of the genera *Homalonatus*, *Cryphaeus*, *Calmonia*, *Proboloides*, *Pennaia*, rarely agreeing fully with their boreal kindred, but usually differing subgenerically, at least. The Cephalopoda are represented by only two species, *Orthoceras* and *Kionoceras*. *Conularia* is abundant, and the Pteropods have one genus *Hyolithus*. Gastropods are not abundant, having only six species. The Pelecypods are abundantly represented by twenty-four species of *Palaeoneilo*, *Nuculites*, *Nuculana*, *Janeia*, *Leptodomus*, *Modiomorpha*, *Sphenotus*, *Pholadella*, etc. The complete absence of the Aviculids and Pterineids shows a sharp contrast with the northern Devonian faunas, as does also the overwhelming development of the Taxodonts (Arcacea) in both numbers and size. The Brachiopods are numerous with twenty-four species of which the most noteworthy are *Spirifer jheringi*, *S. antarcticus*, *S. kayserianus*, and the numerous *Schuchertella*, *Leptostrophia*, *Chonetes*, and Discinacea. There are two starfishes and two sponges. Corals are almost entirely lacking, and Bryozoöns completely so.

The volume is illustrated by twenty-seven beautiful lithographed quarto plates of fossils done in the best style of Werner and Winter of Frankfort, that make the best of half-tones look tawdry in comparison. There are also several excellent text-figures.

Brazil may well be proud of the first volume of the monographs of its geological survey, for it has set an unusually high standard in subject-matter and in mechanical execution.

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